UNIVERSIDADE DE LISBOA

INSTITUTO SUPERIOR TÉCNICO

Risk Management of Coastal Pollution from Oil Spills Supported by Operational Numerical Modelling

Rodrigo Manuel Antunes dos Santos Fernandes

Supervisor: Doctor Ramiro Joaquim de Jesus Neves

Co-Supervisor: Doctor Paulo Miguel Chambel Filipe Lopes Leitão

Thesis approved in public session to to obtain the PhD Degree in

Environmental Engineering

Jury final classification: Pass with distinction

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2018

Abstract

The motivation of this thesis is to assess the ability of contributing to the potential minimization of environmental impacts of vessel-based oil spills at sea, using an integrated approach supported by metocean and advanced oil spill numerical modelling, and through the development of user-friendly, flexible, fast, yet reliable technological solutions. The Portuguese continental coast is defined as the pilot area.

The study aims to test increased response capability to oil spills through efficient decision support tools capable of manually (on-demand) or automatically (triggered by remotely detected oil spills) simulating the trajectory and behaviour of pollutants at sea with a model (MOHID) improved during this research work. It is also intended to assist in the continuous reduction of risk levels of coastal pollution caused by spills through the development of holistic dynamic risk mapping systems which can be used to prioritize and identify points of greater / greatest danger based not only on a historical characterization of the risks, but in real time continuous monitoring as well. The risk model uses multiple data sources, from AIS data, metocean modelling, ship accident statistical information, oil spill modelling and coastal vulnerability.

The typical risk in the pilot area was characterized, as well as the response to different metocean conditions, or to the expected evolution in global shipping (more ships, more tonnage).

The approach, models, tools and the overall results accomplished have demonstrated the usefulness and applicability of advanced numerical modelling for improving decision making in the multiple stages that are involved in emergency and risk management, and thus contributing to an overall improvement of maritime situational awareness. Specifically, the study can improve contingency planning and prevention, intelligent monitoring, preparedness, follow-up and tactical response to incidents, and investigation of possible polluters and quantification of consequences.

Keywords: oil spills, risk management, numerical model, decision support systems, operational oceanography.

Resumo

A tese avalia a capacidade de minimizar potenciais impactes ambientais provenientes de derrames no mar com origem em navios, utilizando uma abordagem integrada suportada por modelação numérica meteo-oceanográfica e de derrames de hidrocarbonetos, e através do desenvolvimento de soluções tecnológicas simples, flexíveis, rápidas e ainda assim fiáveis. O caso de estudo é a costa continental portuguesa.

O estudo visa testar a melhoria da capacidade de resposta aos derrames através de ferramentas de apoio à decisão capazes de simular a pedido ou automaticamente (despoletados por deteções remotas) a trajetória e comportamento de hidrocarbonetos no mar, com recurso a um modelo (MOHID) melhorado no decurso do trabalho. Também se pretende contribuir para a redução do risco de poluição costeira causada por derrames, através do desenvolvimento de sistemas holísticos para mapeamento dinâmico do risco, e que podem ser utilizados na priorização e identificação de pontos de maior perigo, com base não só numa perspetiva histórica dos riscos, mas também com a possibilidade de monitorização em tempo real. O modelo de risco utiliza diversas fontes de informação: dados AIS, modelos meteo-oceanográficos, acidentes passados, modelo de derrames e vulnerabilidade costeira.

O risco típico na área de estudo foi caracterizado, bem como a resposta a variações das condições meteo-oceanográficas, ou à evolução no transporte marítimo (maiores navios, e mais carga transportada por navio).

A abordagem, modelos, ferramentas e os resultados alcançados demonstraram a utilidade e aplicabilidade da modelação numérica na melhoria da decisão na gestão do risco de contaminação por hidrocarbonetos no mar, nas múltiplas fases envolvidas. O trabalho contribui assim para uma melhoria global do conhecimento marítimo situacional. Em específico, o trabalho realizado pode ser utilizado na melhoraria da prevenção e planos de contingência, monitorização inteligente do risco, prontidão, acompanhamento e resposta tática aos incidentes, investigação de potenciais poluidores e ainda quantificação das consequências.

Palavras-chave: derrames de hidrocarbonetos, gestão do risco, modelo numérico, sistemas de apoio à decisão, oceanografia operacional.

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It is a pleasure to thank the many people who made this thesis possible.

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I also thank co-supervisor, Doctor Paulo Leitão. His permanent availability, and his deep knowledge in MOHID processes and source code were vital aspects to the implementation and evolution of the thesis, particularly in the lagrangian and oil spill modelling, but also in the active discussions during the conceptualization of the operational systems.

I am indebted to the many colleagues at MARETEC that provided a stimulating and fun environment in which to learn and to grow, and that were patient with me along time. Above all, a warm and special thanks to Francisco Campuzano, for sharing with me along all these years the stress, the enthusiasm, the emotions and so many fruitful discussions around environmental modelling, operational oceanography, and life in general. Francisco also facilitated the ocean circulation and wave model results that are used across the thesis, which I obviously thank.

I am also thankful to Frank Braunschweig, who has been a key-element in making the whole concept possible to implement, through his coding (super) skills, and pragmatic view of the main challenges. Also, special thanks to Filipe Lourenço and David Brito for collaborating actively to the code implementation of the concepts.

I thank DGAM – SCPM (Serviço de Combate à Poluição do Mar da Direção Geral de Autoridade Marítima), for being supportive and for providing requested data whenever needed. The assistance provided by EMSA, in particular by Anne Marie Hayes, was also important in part of the development process.

An eternal gratitude to my parents, and sister, for their love, help and for pushing me forward through this challenge.

Finally, during this journey, I've shared all my difficulties and states of mind with my wife and partner, Marta. She simply made this possible - and with her by my side, I feel that sky is the limit. Thanks.

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I Introduction

I.1 Statement of the problem

I.1.1 The consequences of oil spills

Oil spills remain one of the most serious environmental risks, as the livelihood and the marine ecosystems can be considerably affected in the event of a significant incident. Over the last 30 years, oil spills have contributed significantly to coastal and marine pollution, causing coastal environmental disturbance.

In fact, consequences range from the biophysical to the social, with both ecosystem and societal impacts, and acute and chronic disturbances (see Figure 1).

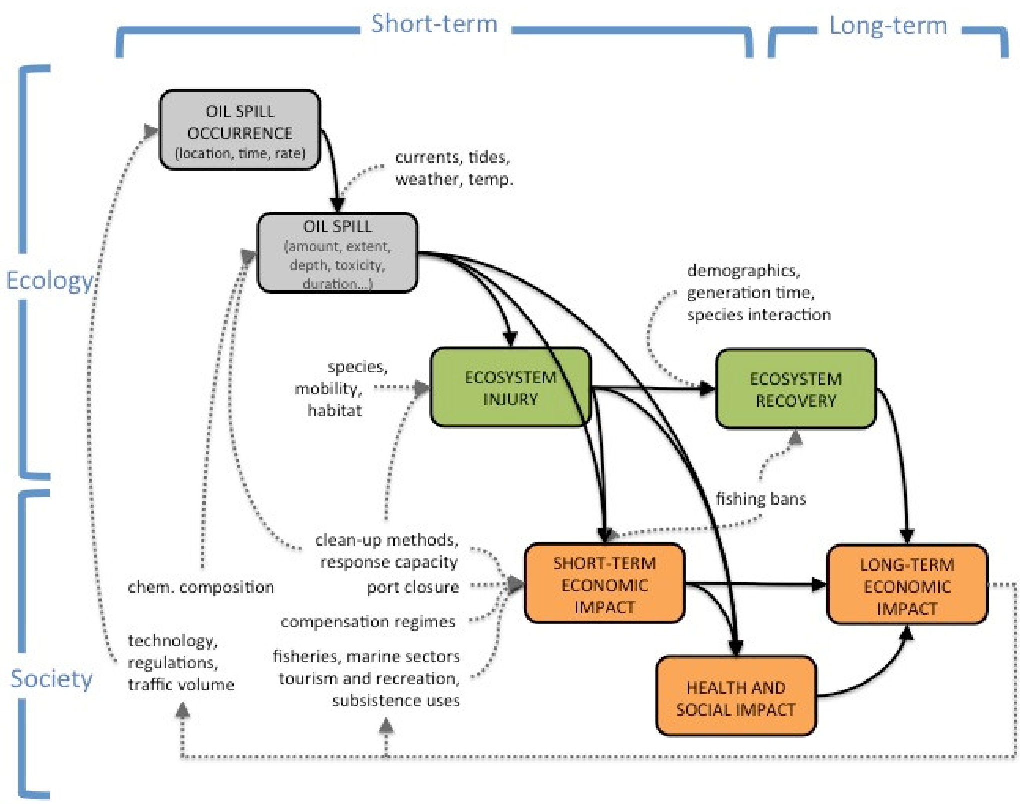


Figure 1 - Oil spill impacts framework. (BOXES = outcomes, lowercasen = variables, solid lines = linkages between oil spill occurrence and socioeconomic impacts, dotted lines= linkages between exogenous variables and outcomes. Grey boxes indicate oil spill outcomes; green boxes, ecosystem consequences; and orange boxes, societal consequences.) (Source: Chang et al., 2014).

Largest oil spill accidents have damaged vulnerable ecosystems around the world, but the severity of a spill is not only connected to the amount released - for instance, the remoteness of the site or the difficulty of an emergency environmental response are factors that can significantly increase the impact.

Oil spills can cause immediate public health impacts, as they represent important fire hazards, and can generate air pollution problems, causing respiratory distress.

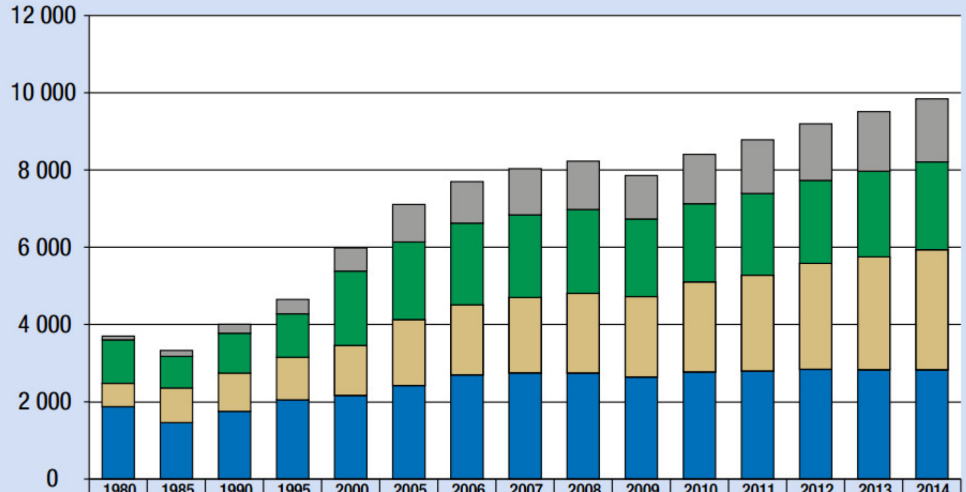
Since clean-up operations, and physical and biological recovery from spills can take weeks, months or even years (Chang et al., 2014; Shigenaka, 2010), oil spills can bring disastrous consequences for society, not only environmentally, but also socially, and economically – particularly when affecting geographical coastal areas highly dependent on tourism and marine resource extraction industries.

Even though mechanical countermeasures are still used extensively to remove and recover oil products, experience shows that recovery rarely retrieves more than 10- 20% of the spilled oil (Linkov and Clark, 2003).

I.1.2 World maritime transport and global shipping

The incidence of maritime pollution with oil spills is frequently linked to ship's accidents. The incidence of large spills from tankers and oil industry operations have become less frequent in the last few decades. Similarly, the huge number of illegal / operational small spills is being progressively controlled and reduced due to the increase in maritime surveillance (e.g. EMSA's CleanSeaNet oil spill detection service). International conventions have provided important preventative measures.

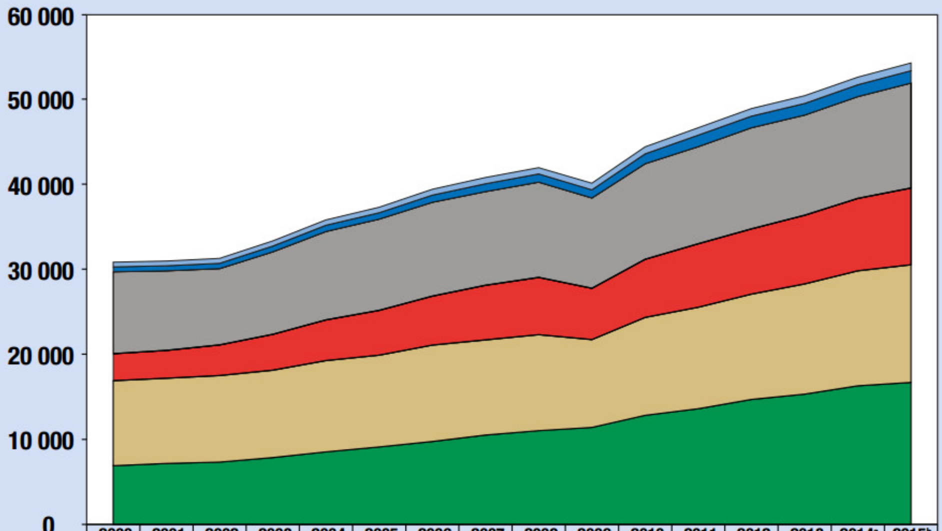
Nevertheless, despite the safety standards increasingly restrictive (double hull, etc.) and surveillance systems much more developed (VTS, AIS, remote sensing), the growing maritime traffic (see Figure 1) and seaborne trade of oil and other hazardous substances makes it difficult to implement a significant reduction of environmental, economic and social risks arising from possible spillage.



	1980	1985	1990	1995	2000	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
Container	102	152	234	371	598	969	1 076	1 193	1 249	1 127	1 280	1 393	1 464	1 544	1631
Other dry cargo	1 123	819	1 031	1 125	1 928	2 009	2 112	2 141	2 173	2 004	2 022	2 112	2 150	2 218	2272
Five major bulks	608	900	988	1 105	1 295	1 709	1 814	1 953	2 065	2 085	2 335	2 486	2 742	2 923	3112
Oil and gas	1 871	1 459	1 755	2 050	2 163	2 422	2 698	2 747	2 742	2 642	2 772	2 794	2 841	2 829	2 826

Figure 2 - International seaborne trade, selected years (millions of tons loaded). Source: UNCTAD, 2015.

Maritime transport is essential to the world's economy as over 90% of the world's trade is carried by sea and it is, by far, the most cost-effective way to move en masse goods and raw materials around the world. Over the past few years there has been also a tendency of increase in the size and volume transported per vessel (see Figure 2), allowing greater economies of scale in transport. Containerization has revolutionized global cargo shipping, bringing vast improvements in efficiency.



	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014[a]	2015[b]
Chemicals	552	562	593	606	625	651	689	724	736	765	824	864	889	908	899	912
Gas	576	591	611	662	719	736	833	913	956	958	1 147	1 344	1 346	1 347	1 382	1 444
Oil	9 631	9 352	8 971	9 698	10 393	10 729	11 036	11 011	11 200	10 621	11 237	11 417	11 890	11 779	11 969	12 339
Container	3 170	3 271	3 601	4 216	4 785	5 269	5 757	6 422	6 734	6 030	6 833	7 469	7 673	8 076	8 514	9 024
Other (minor bulks & other)	9 998	10 023	10 167	10 275	10 729	10 782	11 330	11 186	11 272	10 325	11 504	11 927	12 375	12 952	13 514	13 833
Five main dry bulks	6 896	7 158	7 331	7 852	8 527	9 107	9 745	10 503	11 028	11 400	12 824	13 596	14 691	15 312	16 294	16 685

Figure 3 - World seaborne trade in cargo ton–miles by cargo type, 2000–2015 (billions of ton–miles). a – estimated; b – forecast. Source: UNCTAD, 2015

However, the event of an accident with a supertanker may represent devastating consequences.

I.1.3 The Portuguese context

Portugal has the third largest exclusive economic zone (EEZ) in Europe, and the 20th largest in the world. Multiple ships are constantly present in the Portuguese EEZ. Objectively, approximately 75 000 vessels cross the Portuguese coast every year, with 20% of them carrying pollutants or dangerous substances. This coast is crossed by important international shipping routes with most of the maritime traffic circulating to and from Northern Europe, which gives to Portugal great responsibility in terms of safety of navigation as well as in preventing and combating marine pollution. The geostrategic position of the Portuguese maritime space also presents major challenges in the area of national defence, security and surveillance, such as: illegal immigration, the prevention of pollution, support to navigation and the safe-guarding of human lives at sea.

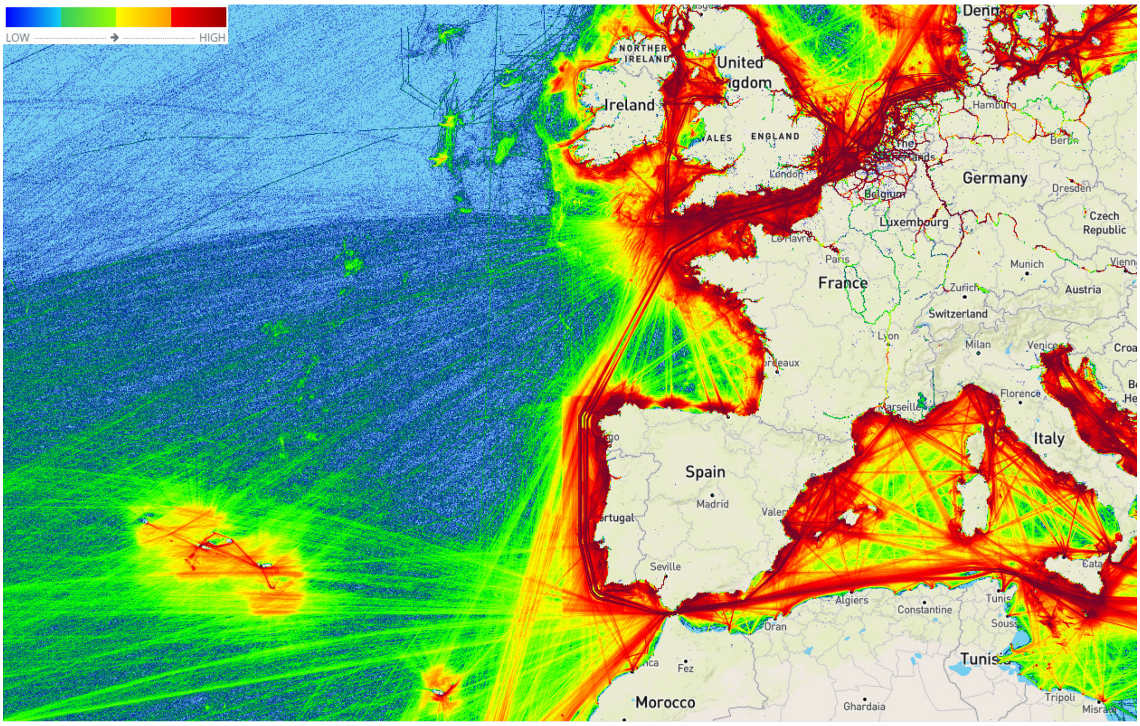


Figure 4 – Shipping density map in the Portuguese coast in 2015 (Source: MarineTraffic)

Portugal has a rich history of seafaring and discovery. With 76% of the population living in coastal areas, Portugal is a country with strong economic dependence of the sea, manifested in the most diverse ways, whether it's fishing, leisure activities, water sports, coastal tourism, or employment associated with the sea economy. The growing importance of tourism in the national economy gives even more importance to the preservation of national coastal zone. The coast attracts 90% of foreign tourists (EC - DG Fisheries and Maritime Affairs, 2016).

Portuguese law (Decree-Law No. 235/2000 of 26 September), reinforced by decisions at Community level (2005/667/JHA and Directive 2005/35/EC) reinforce the sanctions for marine pollution through negligence or attempt. This fact requires the existence of surveillance or analysis tools to support the investigation and identification of pollution sources. Within the framework of the mentioned Directive, operational services were developed to Member States through the European Maritime Safety Agency (EMSA), including the detection of oil spills (CLEANSEANET service) satellite.

It must also be mentioned the Convention for the Protection of the Marine Environment of the North-East Atlantic-OSPAR (ratified on October 31 in Decree-Law No. 59/97), which requires all Contracting Parties to take "all possible measures to prevent and combat pollution, as well as the necessary measures to protect the maritime area against the adverse effects of human activities so as to safeguard human health and to preserve marine ecosystems and, when possible, to restore the maritime areas that suffered these harmful effects ".

More recently, the Lisbon Agreement – the International Centre for combating pollution of the North-East Atlantic (CILPAN) entered in force, with the purpose of helping the contracting parties to react quickly and effectively in the event of an incident of pollution by oil or other harmful substances.

Last, when looking to the map with information of the largest oil spill incidents from tankers (Figure 5), it becomes clear that Portugal is in the vicinity of some important oil spills in the past. Although 19 from the 20 incidents presented in the map didn't affect Portugal, the last one was exactly the Prestige incident. The impact and consequences of Prestige raised the awareness in the European community in general, and for the Iberian citizens in particular, for the environmental and socio-economic aspects that can be affected by these catastrophic events.

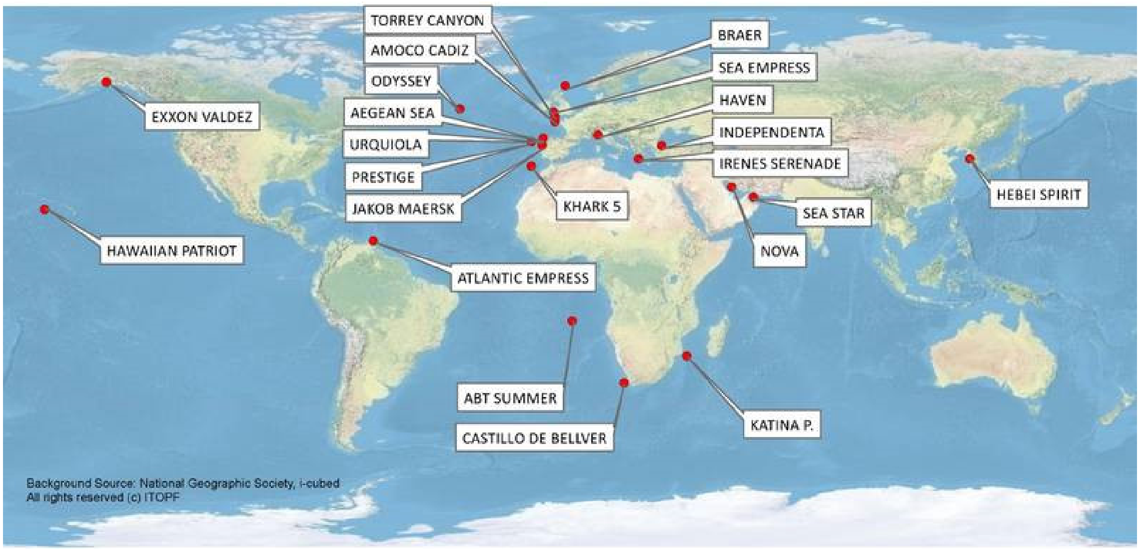


Figure 5 – Tanker top 20 incidents map, since 1967 (Source: ITOPF).

I.1.4 Public awareness and perception

The problems associated with oil spill incidents at sea (and also with inert and HNS - hazardous and noxious substances - even if they are not in scope of work) continues and will continue in the agenda: spill incidents happen, many of them unknown to the ordinary citizen due to its small scale, and few of them (in much smaller number) becoming authentic media phenomena, due to its size, spectacle of images generated, and environmental and socio-economic impact on local communities and ecosystems.

In this "Information Age", where fresh news and social networking are immediately available in mobile phones, tablets, laptops and TV, catastrophic images and news can become viral in a matter of minutes, many times generating outrage, and amplifying risk perception (Sandman, 1987).

These facts remain and increase the pressure to find solutions on all fronts to prevent or minimize the negative result of this type of pollution incidents.

I.1.5 Technological evolution

The evolution in operational observing systems, oceanographic forecasting services, and information systems, created new opportunities and challenges in the emergence and generation of novel integrated and holistic model-based decision support systems, for contingency planning, prevention, follow-up and response to oil spill incidents.

In the last years, new ocean and coastal forecasting capabilities have been achieved and resulted in stabilized operational services (e.g. Copernicus Marine Environmental Services), being now daily accessed and used by several intermediate and final users and downstream services. Since the end of the last century, operational oceanography became one of the most important activities in terms of marine science and technology, and strategically connected to the societal challenges and blue growth agenda promoted in the European Union. Remote sensing is also part of the mentioned operational oceanography. Earth observation services are now able to provide real-time and near-real-time data, rapidly processed, easily accessed, and oriented to multiple integrated maritime services. EMSA's CleanSeaNet is a good example of a near-real-time remote detection monitoring service. Launched and maintained since 2007, this is an important operational service able to provide detected oil spill notifications to the EU Member States in less than 30 minutes (Figure 6).

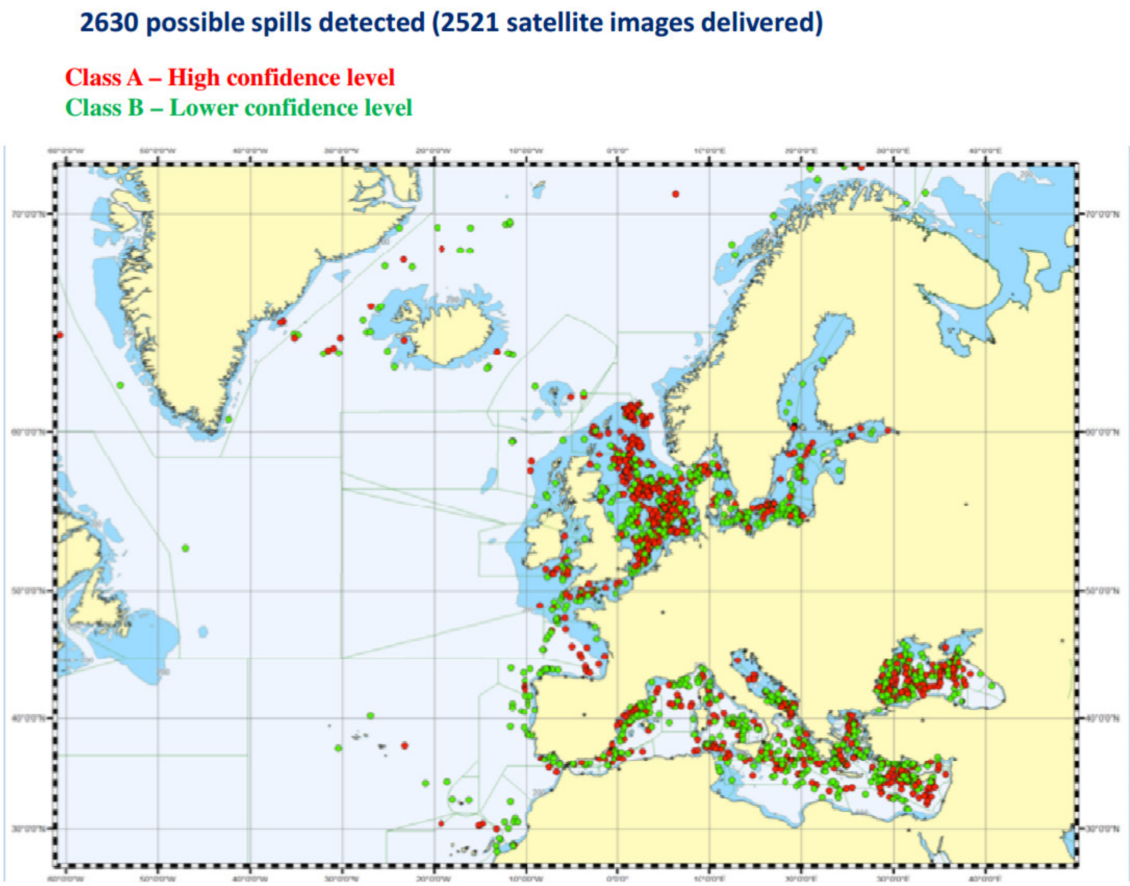


Figure 6 - CleanSeaNet detections in 2014 (Source: EMSA)

Across the last years, other communication technologies and systems have been also explored in the context of maritime surveillance and monitoring. Among them, we can mention AIS, Iridium, Inmarsat, Argos, GPRS. Most of them are now commonly applied by authorities and other institutions, with their data being easily in a global context. A good example is the AIS (Automatic Identification System), a system that became mandatory to be fitted aboard international voyaging ships with gross tonnage (GT) of 300 or more, and all passenger ships regardless of size. The AIS data is now being used not only in Vessel Traffic Services (VTS), but also by open communities (e.g. AISHub) and private business enterprises (e.g. Marinetraffic) for global ship tracking. AIS receiving stations can be easily installed in terrestrial stations, and also in satellites (being called S-AIS).

I.1.6 The links between emergency management, numerical operational modelling and risk analysis

Preventing oil spills is the best strategy for avoiding potential damage to the environment. However, once a spill occurs, the best approach for containing and controlling the spill is to respond quickly and in a well-organized and effective manner. A response will be quick and organized if response measures have been planned ahead of time. Risk analysis of oil spills is an essential step to developing a contingency plan.

Prior to a spill, management entities are required to improve prevention through strategic planning as well as readiness. The main purpose is to minimize the occurrence of spills through more rational management of maritime traffic (VTS monitoring systems, AIS), establishing increasingly rigid and demanding safety standards for the shipbuilding, maintenance and management of vessels; an additional purpose is to intelligently acquire and distribute response and mitigation equipment, also establishing risk maps that are useful in defining the most vulnerable areas and where additional response equipment and prior attention should be focused on maritime surveillance; simulations and drills are also set up to identify gaps in contingency and response plans, as well as to increase the preparedness and experience of those involved.

During a spill, the readiness, response, and tactical approach must be adequately optimized: it is essential to monitor the evolution of the accident through monitoring processes, and from these observations (maritime awareness), to anticipate also the evolution and behaviour of the substances spilled during the next hours and days, with the purpose, for example, to prioritizing the means of response and mitigation in the best possible way. It is also common the task of tracking and identification of the polluting source, although very often the origin is unknown. For this step, remote sensing imagery are commonly used.

After the completion of the spill and response and mitigation measures (in what is usually called the post-spill actions), damage at all levels (socio-economic and environmental) should be assessed with a view to quantifying claims and compensations, as well as assessing the necessary processes to be improved in the future.

The use of numerical modelling tools traditionally occurs in the prevention and strategic / contingency planning phase (before the spills), with the objective of studying typical pollution scenarios, being used in environmental impact studies, or in the preparation of risk maps. Also during and after the spill, the use of modelling systems is common, in order to obtain simulated scenarios to predict the movement and behaviour of the spilled substances. In addition, mathematical modelling can also be used to detect the source of pollutants, mainly through backtracking modelling, with the help of remote sensing images or any other surveillance technologies (e.g. AIS, radars).

However, the resources, complexity and technical-scientific knowledge usually required in the manipulation and use of mathematical models for the simulation of fate and behaviour of pollutant spills at sea, as well as the scarce number of modellers specialized in this area, introduce an increased difficulty in the massive use of the operational application of these instruments in the stages of preparedness and response. Because of these obstacles, decision-makers often resort to use quick and simple application tools - but also generating simplistic and unrealistic scenarios for behaviour simulation and spill drift. These basic applications, most often do not integrate the specific metocean conditions (and the most up-to-date forecasts) for the study area.

The constraints associated with these limitations are several. The main consequence is a deficiency in the decision-making process, either at the level of response time or at the level of the quality of decision-making support itself.

In the preparation of risk maps, it is usual to use a battery of scenarios with constant, typical climatic conditions, among others, as well as the main navigation routes and existing maritime corridors. Another generation of risk maps has recently emerged with the massification of vessel positioning systems, giving rise to the emergence of maps obtained from actual maritime traffic data, some of which intersect this information with coastal sensitivity. These scenarios are very difficult to reproduce real situations, since the meteorological and oceanographic conditions are highly variable spatially and temporally. Additionally, this approach doesn't take into account the trajectory or behaviour of hydrocarbons potentially spilled from ships. Moreover, these scenarios are not dynamic / updated in real time, and none uses the coastal sensitivity that covers the whole Portuguese continental coast.

Deficiencies identified in the calculation of risk maps can lead to biases in the options taken for risk prevention and mitigation measures, such as identifying the best locations for storage of spill response equipment, positioning of combat vessels or tugs or even the positioning of surveillance radars.

I.2 Aim of the thesis

I.2.1 Hypothesis

Based on the context and motivation previously identified, the main question being researched in the ambit of this thesis is:

"Is it possible and viable to minimize the environmental impact of ship-source spill pollution at sea, by means of risk and emergency management supported by numerical modelling, using prompt, simple and simultaneously reliable and rigorous tools?"

In other words, we try to assess and study the ability of potentially minimizing or mitigating environmental impacts, using an integrated approach supported by numerical modelling, and through the development of technological solutions that allow simultaneously their application before (prevention: risk and scenario-based assessment studies; preparedness: dynamic risk monitoring; exercises and drills), after (restoring and environmental impact damage assessment), and specially, during the crisis management (response: tactical and operational support).

I.2.2 Solution

The defined approach will strengthen the bridges between the scientists who master the mentioned mathematical models, and decision makers who need to obtain results quickly and simply, with simulated conditions appropriately adapted to the reality, taking advantage of all the available information at the time of the simulations (including the latest meteo-oceanographic forecasts).

The aim is therefore to create and explore tools to establish these bridges, facilitating and opening doors to an interaction with mathematical models of drift and behaviour (in particular with the lagrangian model of the MOHID system) by decision-makers and stakeholders, in a more efficient and rigorous fashion and taking advantage of the best available information.

The main objective of this work is the development and evaluation of an operational infrastructure composed of novel decision support tools duly adapted to the management of risks related to environmental contamination by oil spilled by vessels, supported by predictive numerical models, and using the Portuguese continental coast as pilot area. It is therefore believed that the proposed solution, tools, and particularly, the oil spill model itself, contribute for a better and more efficient response to the different phases associated with risk management of oil spills at sea, namely: assessment, contingency planning and prevention, continuous monitoring and preparedness, follow-up and response to incidents, and investigation of possible polluters and quantification of consequences. In this way, it is intended to contribute decisively to a reduction of the environmental impacts associated with this type of marine pollution.

The proposed system aims to increase response capability to oil spills through decision support tools capable of automatically tracking detected spills using a drift model, and with the possibility of manually simulating the trajectory and behaviour of pollutants at sea. Indeed, in the context of this work, it is believed that with the current technological level available, it is possible to develop an on-demand spill simulation system that will eliminate the constraints identified above.

It is also intended to assist in the continuous reduction of risk levels of coastal pollution caused by spills through the development of holistic dynamic risk mapping systems which can be used to prioritize and identify points of greater / greatest danger based not only on a historical characterization of the risks, but in real time continuous monitoring as well.

I.3 Outline

Chapter II describes the methodological approach followed in this work. The first (and main) object of study under the thesis is the improvement of the simulation of the trajectory and behaviour of pollutants spilled at sea. The oil spill drift and behaviour model improved and applied throughout the thesis is the MOHID model (whose oil spill model was previously developed by the author). A detailed technical description of the final version of MOHID oil spill model (accomplished at the end of this thesis) is included. The complete description is included as an annex (Annex 1), and this information can later be easily adapted as a new technical and scientific comprehensive manual for the new version of MOHID oil spill model. A brief overview on operational modelling and oil spill risk assessment is also included in this chapter, as those were specific topics of great importance in the development of the research presented.

Chapter III focus on the efforts done in terms of developing spill trajectory and weathering modelling for operational purposes, materialized with two published papers.

The first one (III.2- "Integration of an Oil and Inert Spill Model in a Framework for Risk Management of Spills at Sea") presents a comprehensive literature review of the existing and most popular oil spill drift and behaviour models, as well as of oil spill operational modelling systems. The research paper includes description of specific updates and improvements in MOHID instrument in the context of operational modelling, including new processes such as subsurface movement of oil droplets (entrainment and ascending movement), oil droplet diameters dispersed in the water column, Stokes drift, container drift and drifting buoys with submerged drogue, as well as updating and optimization of already simulated processes (for example, oil-shoreline interaction, new equations for the calculation of emulsification, etc.). Some of the features were tested and compared to field data (e.g. drifting buoys data). This paper also describes and applies new operational capabilities, including backtracking simulation feature, as well as the new MOHID model ability of simulating lagrangian trajectories using more than one meteo-oceanographic solution simultaneously, and through real-time interpolation, facilitating the operational modelling and making the system agnostic regarding the forcing used. Finally, this research paper materializes and illustrates the ability of integration of the MOHID oil and inert spill model in specific operational decision support systems.

A second published paper is included in this chapter (III.3 - “A new modelling toolkit for managing oil and chemical spills in Western Europe and Morocco’s Atlantic coast: the Lisbon Agreement and MARPOCS project”). Among other aspects, this methodological paper describes the approach followed for the implementation of a “Multinational Response and Preparedness to Oil and Chemical Spills”, making use of MOHID oil spill model developed as well as the newly developed chemical spill model (out of the scope of this thesis). This is the most recent example of a materialization of the solution proposed under this thesis, consisting in the implementation of a common operational framework supported with model-based decision support systems, adapted to the region of study and involving cross border cooperation, implementation and training of local, regional and national authorities. The paper also provides a small description and preliminary results of some of the on-going development in terms of decision support systems comprehensively described in other chapters (e.g. automatic early warning forecasting system for oil spills – Chapter IV.1; shoreline holistic risk mapping – Chapter V).

Chapter IV is related mainly with the integration of the oil spill module being studied in the context of risk management, in association with remote sensing. In that sense, a published paper is included, called “Automated system for near-real time prediction of oil spills from EU satellite-based detection service”. Based on EMSA’s CleanSeaNet operational service, an automatic and operational oil spill forecasting service is fully described and implemented. In addition, and also based on MOHID oil spill model and EMSA’s CleanSeaNet historical detections from the previous years, an oil spill hazard assessment for the whole Portuguese continental coast is included.

Chapter V is related with the conceptual design, development and application of a new methodology for analysing the risk of coastal contamination. This chapter is divided by three main sections or papers.

The first section (V.2 - “Quantifying coastal sensitivity to oil spills for risk assessment purposes”) consists on the description and implementation of a coastal sensitivity classification in the context of oil spills, for the Portuguese continental coast. This classification is divided in different coastal sensitivity indices, that are then able to be integrated in risk assessment studies (which has been done in the risk model developed in the following section).

The second section (V.3 - the published work "Combining operational models and data into a dynamic vessel risk assessment tool for coastal regions") describes the full concept and methodology behind the novel shoreline holistic risk mapping tool based in oil spills from vessels, as well as providing sensitivity analysis to evaluate the relative effect of some metocean parameters in the final results.

The third section (V.4 - "Assessing oil spill risks from vessels in the Portuguese continental coast using a holistic modelling approach") provides a comprehensive risk assessment in the area of study, benefiting from the holistic risk tool developed above. This risk characterization includes not only an historical analysis (vessel traffic info and metocean conditions from 2013), but also a scenario-based risk assessment, based on expected evolutions and trends in global shipping industry (increasing vessel sizes), or in climate change scenarios (e.g. decreasing wave height).

The last chapter VI contains all the concluding remarks, the major contributions from the author and the thesis, and considerations for future research.

I.4 Individual contributions

A significant number of chapters of this thesis is materialized in the form of published or submitted peer-reviewed papers, where multiple co-authors have contributed to the final results.

Here I detail my specific contributions to those papers.

In Chapter III.2 ("Integration of an Oil and Inert Spill Model in a Framework for Risk Management of Spills at Sea: A Case Study for the Atlantic Area"):

- Full writing of the paper;
- Bibliographic review in oil and inert drift modelling decision support systems;
- Conceptual design of EASYCO Web Bidirectional Tool and ARCOPOL Offline Spill Simulator (configuration of model inputs and outputs, pre-definition of spill model, and definition of user interface – inputs, outputs, and option for tabbed wizard interface);
- Conceptual design of the dynamic risk tool (algorithm for risk modelling; definition of inputs and outputs); programming and adapting algorithm for risk modelling inside MOHID Studio; configuration of oil spill modelling;
- Programming and implementation (in lagrangian model) of floating container model; feature of drifting buoys with subsurface drogues; wave-driven induced velocity (Stokes drift) and subsurface vertical movement of entrained oil; review on formulations for weathering processes;
- Coordination of the field work with drifting buoys in the Tagus estuary Mouth; model running for calibration and validation;
- Running oil spill model in the oil spill exercise in Sesimbra;
- Automatic and operational management software (ART- Automatic Running Tool) for the metocean modelling network (although metocean models were not implemented by me).

In Chapter III.3 ("A New Modelling Toolkit for Managing Oil and Chemical Spills in Western Europe and Morocco's Atlantic Coast: The Lisbon Agreement and MARPOCS Project"):

- Full writing of the paper;
- Methodological implementation of the modelling framework;

- Improvement of the oil spill model (interaction with scientists from MEOPAR project for correct quantification of jet / near field plume dynamics of underwater oil released in the subsea; probabilistic maps from ensemble forecasts with perturbed parameter schemes; toxicological risks and impacts from spills);
- Development and integration of a chemical spill model in MOHID;
- Conceptual design of MARPOCS Common Operating Picture and ACTION Seaport Decision Support Systems (configuration of model inputs and outputs, pre-definition of spill model, and definition of user interface – inputs, outputs, and option for tabbed wizard interface);
- Design, programming and implementation of the MOHID-CLEANSEANET automatic early warning forecasting system;
- Conceptual design of the dynamic risk tool / shoreline holistic risk mapping; programming and adapting algorithm for risk modelling; configuration of oil spill modelling (this work has already been referenced in the previous paper);
- Automatic and operational management software (ART- Automatic Running Tool) for the IST metocean modelling network (although metocean models were not implemented by me) (this work has already been referenced in the previous paper).

In Chapter IV.1 ("Automated system for near-real time prediction of oil spills from EU satellite-based detection service"):

- Full writing of the paper;
- Design, programming and implementation of the MOHID-CLEANSEANET automatic early warning forecasting system (as referenced in the previous chapter);
- Automatic and operational management software (ART- Automatic Running Tool) for the metocean modelling network (although metocean models were not implemented by me) (this work has already been referenced in the previous paper);
- Development of the oil spill hazard analysis (although the map visual representation was generated by another co-author).

In Chapter V.2 ("Quantifying coastal sensitivity to oil spills for risk assessment purposes"):

- Full writing of the paper;
- Creation and implementation of socio-economic and ecological indices in Portugal;
- Exporting all the coastal sensitivity indices (environmental, socio-economic and ecological) to GIS formats (shapefiles, Google Earth).

In Chapter V.3 ("Combining operational models and data into a dynamic vessel risk assessment tool for coastal regions"):

- Full writing of the paper;
- Conceptual design of the dynamic risk tool / shoreline holistic risk mapping; programming and adapting algorithm for risk modelling; configuration of oil spill modelling (this work has already been referenced in a previous paper);
- Automatic and operational management software (ART- Automatic Running Tool) for the metocean modelling network (although metocean models were not implemented by me) (this work has already been referenced in the previous paper);
- Sensitivity analysis performed to the risk model.

In Chapter V.4 ("Assessing oil spill risks from vessels in the Portuguese continental coast using a holistic modelling approach"):

- Full writing of the paper;
- Conceptual design of the dynamic risk tool / shoreline holistic risk mapping; programming and adapting algorithm for risk modelling; configuration of oil spill modelling (this work has already been referenced in a previous paper);
- Automatic software for the management of the metocean models (ART- Automatic Running Tool) (although metocean models were not implemented by me) (this work has already been referenced in the previous paper);
- Development and execution of the risk model analysis.

I.5 Dissemination

Papers published, submitted or in preparation to peer-reviewed international journals or peer-reviewed international conferences included in this thesis:

- Chapter III.2: Fernandes, R., R. Neves, C. Viegas, and P. Leitão, *Integration of an Oil and Inert Spill Model in a Framework for Risk Management of Spills at Sea: A Case Study for the Atlantic Area*, Proceedings of the Thirty-sixth AMOP Technical

Seminar on Environmental Contamination and Response, Environment Canada, Ottawa, ON, pp. 326-353, 2013.

- Chapter III.3: Fernandes, R., R. Neves, C. Viegas, and P. Leitão, *A New Modelling Toolkit for Managing Oil and Chemical Spills in Western Europe and Morocco's Atlantic Coast: The Lisbon Agreement and MARPOCS Project* (2016). Proceedings of the Thirty-ninth AMOP Technical Seminar on Environmental Contamination and Response, Environment Canada.
- Chapter IV.1: Fernandes, R., F. Campuzano, D. Brito, M. Juliano, F. Braunschweig, and R, Neves (2017). *Automated system for near-real time prediction of oil spills from EU satellite-based detection service.* International Oil Spill Conference Proceedings: May 2017, Vol. 2017, No. 1, pp. 1574-1593.Fernandes, 2016 Ocean Science.
- Chapter V.2: Fernandes, R., Santos, M. Quantifying coastal sensitivity to oil spills for risk assessment purposes. In preparation to Marine Pollution Bulletin.
- Chapter V.3: Fernandes R, Braunschweig F, Lourenço F, Neves R. (2016). *Combining operational models and data into a dynamic vessel risk assessment tool for coastal regions.* Ocean Science 12.1 : 285-317.
- Chapter V.4: Fernandes, R., Braunschweig, F., Campuzano, F., Neves, R., *Assessing oil spill risks from vessels in the Portuguese continental coast using a holistic modelling approach.* In preparation to Human and Ecological Risk Assessment.

Other published papers in peer-reviewed international journals or peer-reviewed international conferences:

- Mateus, M., G. Riflet, P. Chambel, L. Fernandes, R. Fernandes, M. Juliano, F. Campuzano, H. de Pablo and R. Neves (2012). “An Operational Model for the West Iberian Coast: Products and Services", Ocean Science, 8: 713-732, 2012.
- Juliano, M.M.F., R. Neves, P.P.G.W. Rodrigues, J.L. Junior, R. Fernandes (2012). Aplicação da Plataforma MOHID para simulação computacional de deriva oceânica de petróleo na bacia de campos – RJ, Boletim do Observatório Ambiental Alberto Ribeiro Lamego, Campos dos Goytacazes/RJ, v. 6 n. 1, pp. 161-172
- Ascione Kenov, I., Campuzano, F., Franz, G., Fernandes, R., Viegas, C., Sobrinho, J., de Pablo, H., Amaral, A., Pinto, L., Mateus, M., Neves, R. (2014).

Advances in Modeling of Water Quality in Estuaries, in: Finkl, C.W., Makowski, C. (Eds.), Remote Sensing and Modeling. Springer International Publishing, pp. 237-276

- Muttin, F., Priour, D. and Fernandes, R. (2014) Session 1: Structures, Materials and the Environment, in Marine Coastal and Water Pollutions (ed F. Muttin), John Wiley & Sons, Inc., Hoboken, NJ, USA. doi: 10.1002/9781119003021.ch1
- Campuzano F, Brito D, Juliano M, Fernandes R, de Pablo H, Neves R. (2016). Coupling watersheds, estuaries and regional ocean through numerical modelling for Western Iberia: a novel methodology. Ocean Dynamics. 2016: 1-12.

Short papers, conference abstracts, proceedings and communications:

- Pinto, L., F.J. Campuzano, R. Fernandes, L. Fernandes and R. Neves, (2012). "An Operational Model for the Portuguese Coast", in Actas das 2ªs Jornadas de Engenharia Hidrográfica, Lisboa, pp. 85-88.
- Campuzano, F.J., R. Fernandes, P.C. Leitão, C. Viegas, H. de Pablo and R. Neves, (2012). "Implementing local operational models based on an offline downscaling technique: The Tagus estuary case", in Actas das 2ªs Jornadas de Engenharia Hidrográfica, Lisboa, pp. 105-108.
- Fernandes, R., P.C. Leitão, F. Braunschweig, F. Lourenço, P. Galvão and R. Neves, (2012). "Using Numerical Models in the Development of Software Tools for Risk Management of Accidents with Oil and Inert Spills", in Proceedings of EGU General Assembly 2012, Vienna, Austria, p. 10550.
- Fernandes, R., P. Galvão, F. Lourenço, C. Viegas and R. Neves, (2012). "Modelação de Derrames de Poluentes: Desenvolvimento e Integração na Nova Geração de Ferramentas de Apoio à Decisão", in Actas do 11º Congresso da Água.
- Lourenço, F., F. Braunschweig, R., Fernandes, (2012). "A Framework for Real Time Coastal Risk Evaluation", in Livro de Resumos do VII Encontro Nacional de Riscos e I Fórum sobre Riscos e Segurança do ISCIA, Aveiro, Abril 2012.
- Fernandes, R., R. Neves, F. Lourenço, F. Braunschweig (2013), "Forecasting the Risks of Pollution from Ships along the Portuguese Coast", in Proceedings of EGU General Assembly 2013, Vienna, Austria, Geophysical Research Abstracts, Vol. 15, EGU2013-6592.

- Pinto L, Campuzano FJ, Juliano M, Fernandes R, Neves R. (2014). Implementation and validation of an operational model for the Portuguese exclusive economic zone. 3.as Jornadas de Engenharia Hidrográfica, Lisbon, Portugal. Extended abstracts: 107-110.
- Fernandes, R. (2014). A new modelling tool for chemical spill modellers and responders. 7th EUROGOOS Conference Proceedings. Lisbon, 28-30.
- Fernandes, R., Filipe Lourenço, Frank Braunschweig, and Ramiro Neves (2014) Dynamic Risk Assessment of Shoreline Contamination from Ships: Integrating an Oil Spill Model. International Oil Spill Conference Proceedings: May 2014, Vol. 2014, No. 1, pp. 299678.
- Rose Campbell, Frédéric Muttin, Rodrigo Fernandes, Ligia Pinto, and Guilherme Franz (2014). Modelling Oil Spill Containment in Coastal Areas. International Oil Spill Conference Proceedings: May 2014, Vol. 2014, No. 1, pp. 299742.
- Fernandes, R., Francisco Campuzano, Manuel Juliano, Frank Braunschweig, Ramiro Neves (2015). "Gestão de Emergências em Zonas Costeiras", in VIII Congresso sobre Planeamento e Gestão das Zonas Costeiras dos Países de Expressão Portuguesa, Aveiro. Artigo 118.
- Campuzano F, Brito D, Juliano M, Sobrinho J, Fernandes R, Pinto L, Neves R. (2015). Integração espacial e temporal por métodos numéricos dos processos associados às bacias hidrográficas, estuários e oceano regional para a costa ocidental da Península Ibérica. VIII Congresso sobre Planeamento e Gestão das Zonas Costeiras dos Países de Expressão Portuguesa. Aveiro, Portugal. Artigo 114.
- Li, P., Niu, H., Fernandes, R., Neves, R. (2016). A Coupled Deepwater Jet and Hydrodynamic Model for Near- and Far-field Simulation of Oil Spilled from Deepwater Blowout. Proceedings of the Thirty-ninth AMOP Technical Seminar on Environmental Contamination and Response, Environment Canada, Ottawa
- Brito, D., Fernandes, R., Braunschweig, F., Braunschweig, S., Campuzano, F., Trancoso, A.T. (2016). An integrated framework for implementing operational coastal models, 4as Jornadas de Engenharia Hidrográfica.
- Fernandes, R., Brito, D., Braunschweig, F., Trancoso, A.T., Campuzano, F. (2016). Assessing the impact of meteorological models in coastal and estuarine surface drift forecasting systems, 4as Jornadas de Engenharia Hidrográfica.

- Fernandes, R., Brito, D., Braunschweig, F. (2017b). "Plataforma holística para melhoria de performance ambiental, operacional e de segurança portuária: Aplicação no Porto de Lisboa"., 9as Jornadas Portuguesas de Engenharia Costeira e Portuária, LNEC.
- Pu Li, Haibo Niu, Shihan Li, Rodrigo Fernandes, and Ramiro Neves (2017). A Comprehensive System for Simulating Oil Spill Trajectory and Behaviour in Subsurface and Surface Water Environments. International Oil Spill Conference Proceedings: May 2017, Vol. 2017, No. 1, pp. 1251-1266.

II Methodological approach

II.1 Overview

This brief chapter describes the broad theoretical and conceptual aspects related with the approach taken in the three main central topics of this thesis: oil spill modelling, operational modelling, and risk assessment. Special focus is put on oil spill modelling. Hence, the chapter sections gather generic or comprehensive (in the case of oil spill modelling) background information on those topics, showing how some of this information and methodologies were adopted in the course of the work. The chapter works as an aggregative complement to the bibliographic reviews and methodological descriptions included in the papers / manuscripts from chapters III, IV and V.

II.2 Modelling oil spills

Oil spill modelling is the central point of this thesis, being an integrative part of all the items and tools analysed and developed. The following sections compile the state-of-the-art in terms of oil spill modelling know-how, and explain how this knowledge is transported to the adopted modelled approach.

During the course of this thesis, the oil spill modelling system adopted (initially developed by Fernandes, 2001) was deeply reviewed and updated in order to expand and improve its prediction capabilities, and to be in agreement to the present state-of-the-art in terms of oil spill modelling. Nevertheless, the system is dynamic and still continues to evolve, as a result of on-going collaborations with other researchers and universities.

II.2.1 Fate and behaviour of oil spills

Once released in the aquatic environment, oil products can behave differently, depending on the physical and chemical properties of the released oil products, and in the metocean conditions of the receiving environment. The weathering of an oil spill at sea are illustrated in the Figure 7.

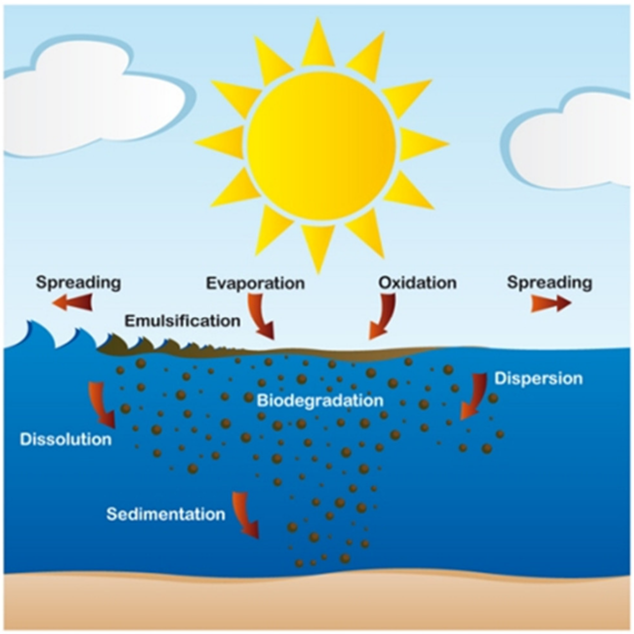


Figure 7 - Fate of oil spilled at sea showing the main weathering processes. Source: ITOPF

The diagram below (Figure 8) represents the weathering fate of a typical crude oil spill (type 2 / 3), showing changes in the relative importance of weathering process with time (from hours to years). The width of the band indicates the relative importance of the process.

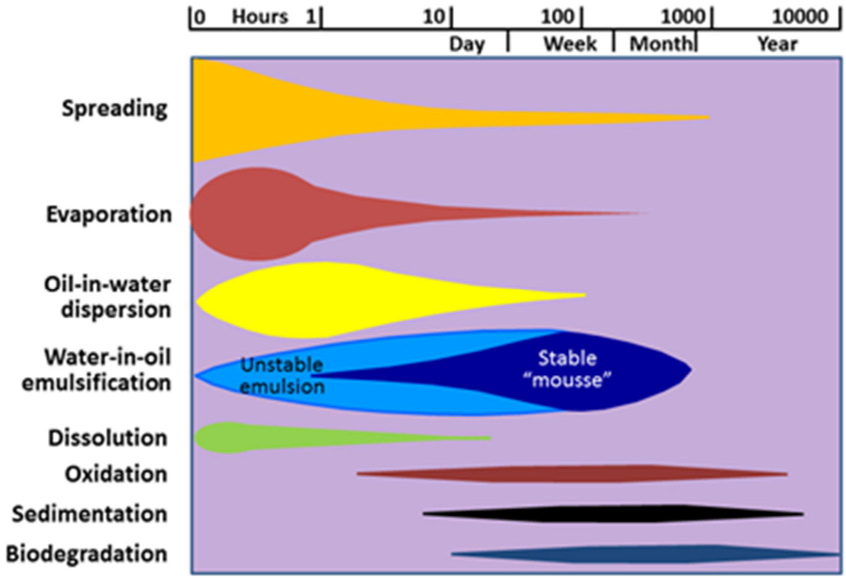


Figure 8 – Weathering processes of a typical crude oil. Source: AMSA (courtesy of SINTEF).

II.2.2 Numerical model approach adopted

In order to predict the behaviour of spilled oil products, an oil weathering model is used, which predicts the evolution and behaviour of the processes and properties of the oil product spilled in water.

The oil spill fate and behaviour (physical-chemical behaviour and trajectory) model is integrated in lagrangian module of MOHID (a public-domain / open-source water modelling system – www.mohid.com).

II.2.2.1 MOHID suite

The main advantage of using an oil spill fate and behaviour model that is an integral part of MOHID is the possibility of using several different properties, processes and features already developed and tested in other types of modelling applications.

MOHID (Neves, 2013) is a three-dimensional water modelling system, developed by MARETEC (Marine and Environmental Technology Research Center) at Instituto Superior Técnico (IST) which belongs to Technical University of Lisbon. This modelling system allows the adoption of an integrated modelling philosophy, not only of processes (physical and biogeochemical), but also of different scales (allowing the use of nested models) and systems (estuaries, watersheds, open-sea, rivers), due to the adoption of an object-oriented programming philosophy.

MOHID has been applied to different study cases, as coastal and estuarine areas, as well as oceanic processes and reservoirs, and it has showed its ability to simulate complex features of the flows (Ascione Kenov et al., 2014).

II.2.2.2 Lagrangian component of MOHID

The MOHID model uses the concept of lagrangian tracers to simulate the spatial-temporal evolution of localized processes with sharp gradients (e.g. submarine outfalls, sediment erosion due to dredging works, hydrodynamic calibration, and also oil spill), determined by multiple metocean conditions, including tidal regime and local circulation. Each tracer has the ability to be associated with one or more properties (physical, chemical or biological). This model is a subset of the MOHID modelling system and has been used in other instances also to study pollutant dispersion (Ascione Kenov, et al., 2014). MOHID Lagrangian transport module assumes that the spilled contaminant (or water mass) can be represented as an amount of several different small tracers / spillets, and tracked as they move in three-dimensional space over time.

This software is presently used in several different studies, not only oil spills, but also floating containers, harmful algal blooms (Mateus et al., 2012), fish larvae (Nogueira et al., 2012), residence time in estuaries (Braunschweig et al., 2003, Kenov et al., 2012), faecal contamination in bathing waters and plume diffusion and dispersion (near and far field) in water column from submarine outfalls or rivers (Miranda et al., 1999; Viegas et al., 2009; Viegas et al., 2012), sediments transport, etc.

MOHID lagrangian module can be run simultaneously with the hydrodynamic model (currents, water temperature, salinity, etc.), or in "offline" mode. In both modes, this model is able to digest currents, water properties, wave parameters and atmosphere properties from different model providers.

During the course of this thesis, the lagrangian module was also adapted to allow backtracking simulation, in order to facilitate identification of pollution sources. This implementation was done simply by changing the sign of terms describing explicit advection, and any terms describing linear sources or sinks are kept unchanged, as well as the turbulent diffusion.

II.2.2.3 Oil spill module of MOHID

In order to predict the fate of oil products spilled in coastal zones, the oil weathering model predicts the evolution and behaviour of the oil intrinsic processes (transport, spreading, evaporation, etc.) and properties (density, viscosity, etc.) of the oil products. Oil density and viscosity, and many different processes such as oil spreading, evaporation, dispersion, sedimentation, dissolution and emulsification, have been included in the oil module.

Except for the spreading and oil-beaching, all weathering processes and properties are assumed to be spatially uniform for all tracers, like water properties and atmospheric conditions. These are assumed to be equal to the environmental conditions at spill "origin" (release point). Oil temperature is assumed equal to water temperature, neglecting solar radiation or any other energy transfer process that may influence oil temperature. In its preliminary version,

For each spill "origin", the model estimates the global oil mass budget evolution along time, identifying and quantifying in each output time the lost mass in weathering processes (evaporation, dispersion, dissolution, sedimentation), the water content (emulsification), as well as the oil properties evolution, like density and viscosity.

MOHID oil spill modelling component was initially developed in 2001 by the author (Fernandes, 2001), and along all these years the model has been improved and operationally applied in different applications (Balseiro et al., 2003; Carracedo et al., 2006; Janeiro et al., 2008; Mateus et al., 2008; Pierini et al., 2008), including incidents, field exercises and studies worldwide.

At the beginning of this thesis, MOHID OWM was not a full 3D application, simulating the amount of oil that leaves the water surface (by different processes like evaporation, or dispersion in water), without simulating the evolution at the subsurface and variations in the water column (including both oil entrainment and resurfacing).

Processes and properties considered in MOHID oil spill fate and behaviour model

The most important oil physical and chemical transformations, as well as transport processes, have been included in MOHID.

Simulated processes include (three-dimensional) advection, spreading (on floating oil products), turbulent (vertical and horizontal) diffusion, evaporation from surface and consequent atmospheric transport, natural dispersion (droplets entrainment + submergence), dissolution, sedimentation (adsorption to sediments), and shoreline interaction. The significance of sedimentation as an important removal process depends critically on the sediment load of the surrounding water (typically, in open ocean, removal by sedimentation is trivial). Degradation (biodegradation and photo-oxidation) processes are not included in the model. Degradation can be considered significant only after the first week of simulation (Fernandes, 2001), which can be seen in Figure 8. For most oils, photo-oxidation is not a very well-known process, and is not considered an important process in terms of changing their immediate fate or mass after a spill. Biodegradation is not considered an important weathering process in the short term as well (Fingas, 2011a). The modelled oil properties along the simulation are the density and viscosity.

During the course of this thesis, several oil transport and weathering processes were either included, revisited, or adapted. The most relevant new processes added to MOHID oil spill model include the wave-induced currents (Stokes drift), leeward drift angle, dynamic estimation of wind drift coefficient, oil droplet 3D vertical movement (entrainment, resurfacing), atmospheric transport of evaporated fraction. New or newer formulations were included for evaporation, emulsification, shoreline interaction. The simulation of blowout emissions was also included in the model. Although this implementation was out of the scope of this thesis (Leitão, 2013), the simulation of this process was also improved by the work of the thesis, due to the new available formulations to compute oil droplet sizes and their ascending velocity.

The algorithms, assumptions and detailed processes associated to MOHID oil spill model are fully described in Annex 1.

II.3 Operational modelling

A major objective of this thesis is to develop and demonstrate an oil spill model capable of supporting and improving multiple decision making in the multiple phases of emergency and risk management. In the stages involving prevention and preparedness, as well as follow-up and response to an accident, the capacity of providing easy, fast and reliable oil spill fate and behaviour forecasts is particularly relevant on the decision making. This forecasting ability can be defined as the operational modelling capacity. The operational modelling capacity involves more than simply implementing an automatic simulation system, and / or having the possibility of running on-demand simulations. Operational modelling includes a complex articulation of different multiples stages, involving transmission of observational data, integration of initial, boundary and forcing conditions into accurate modelling systems capable of providing realistic real-time simulations and forecasts. By other words, operational oceanography includes making, disseminating, and interpreting measurements of the seas and oceans in order to provide forecasts of future conditions (Prandle, 2000).

One of the challenges is exactly to provide these realistic forecasts in the shortest period of time. This challenge has been faced along the last decades in operational oceanography, with the last 20 years representing significant scientific and technological advances in this matter (She, et al, 2016). The requirements associated to fast and reliable operational forecasting systems involve all the traditional aspects needed in numerical modelling: a) correct definition of initial, boundary and forcing conditions; b) a model able to properly resolve small-scale features and events needed for operational services; c) a modern and powerful computational infrastructure to run the modelling system. Nevertheless, these conditions may not be enough to serve the purpose of providing fast simulations. The model must also have a high coding standard, flexible grid and efficient numerical schemes to meet computational needs of operational forecasting. The integration of parallel processing schemes can also contribute to improve the overall efficiency of the computational process, having in mind that parallel computing (in both central and graphic units) became dominant paradigm in computer architecture, mainly in the form of multi-core processors, but also in clusters, and more recently with GPU technology.

The adoption of MOHID lagrangian component for this work has already been described and justified in section II.2.2. Moreover, this model embraces all the main operational requirements mentioned above, although parallel computing was not implemented in the MOHID lagrangian component yet (MPI and OpenMP parallel computing directives were already implemented in MOHID Water and MOHID Land generic models, as well as GPU in specific parts of the code).

Operational metocean models need also to be integrated as forcing conditions of the oil spill modelling system. Parallel efforts have been done during the work of this thesis to configure, validate and implement a set of operational wave, weather and ocean coastal circulation models in the areas of study (Mateus et al., 2012; Trancoso, 2012; Pinto et al., 2012; Franz et al., 2014; Campuzano et al., 2016). These efforts have given the opportunity to develop adequate operational oil spill modelling systems capable of performing in live testing environments.

II.4 Oil spill risk assessment

Risk analysis of oil spills is an essential step of developing contingency plans. It is not only the basis of oil spill risk assessment, but also the basis of decision making about treating risks.

The purpose of risk assessment is to evaluate the extent of the influence of environmental contamination and physical disturbances on humans and biota; and then, coupled with the use of risk management objectives, to guide environmental decisions so as to minimize risk to receptors while maximizing economic and social benefits (Linkov and Clark, 2003).

The occurrence of oil spills is fundamentally a matter of probability. There is no certainty regarding the amount of oil that would be produced, or the size or likelihood of a spill that would occur. A probabilistic event such as an oil-spill occurrence or oil-spill contact to an environmentally sensitive area cannot be predicted, only an estimate of its likelihood (its probability) can be quantified.

Hence, risk analysis involves consideration of the sources of risk, their consequences and likelihood that those consequences may occur. The consequences and likelihood of each risk source determines the level of risk. It is inappropriate to assume that the quantitative is always better than qualitative analysis. Risk analysis may be undertaken to varying degrees of detail depending upon the risk, the purpose of the analysis, and the information, data and resources available (Zhang, 2006).

For developing contingency plans, the objectives of oil spill risk analysis are as follows:

- Measuring the risk levels and understanding its nature;
- Prioritising the risk (as it will not be possible to give equal protection to all sensitive resources);
- Making decision of risk-reduction measures.

Oil spill hazards connected to the transport phase need to be evaluated carefully, considering both environmental and accident risk (Fabiano et al., 2002).

This recurrent hazard has increasingly been addressed through prevention plans and integrated coastal zone management. Numerous studies have attempted to analyse vulnerable areas and the impacts of oil pollution. Operational tools have also been widely developed to classify coastlines within the context of oil spill management. These tools include sensitivity or vulnerability maps of coastal and offshore areas in many countries (Danchuk and Willson,2010; Fattal et al., 2010; Ihaksi et al., 2011).

Oil spill risk assessment methodologies are usually directly linked to execution of multiple oil spill trajectory simulations in different locations, under different metocean conditions and for different time periods (e.g. 3, 10 or 30 days). Trajectories are then integrated and compiled in terms of frequencies in order to identify the most affected geographical areas, i.e., the locations or geographical boundaries that where crossed more frequently by the oil trajectories (Price et al., 2003; Ji et al., 2003).

Risk analyses may be characterized as "hazard-based" or "risk-based." A hazard-based analysis examines possible events regardless of their low (or high) likelihood, and without quantifying the expected impact. For example, a potential impact (hazard) would not lose significance because the risk has been reduced due to an increase in the level of control, such as implementing surveillance systems (and thus reducing the likelihood). A risk-based analysis, on the other hand, does take into account the likelihood of the event occurring, the coastal sensitivity, or the measures that can be taken to mitigate against its potential impacts.

The approach followed in this work for the shoreline risk assessment is risk-based, in the sense that likelihood (probability of vessels having a spill) is taken in consideration, as well as the social, economic and environmental consequences (coastal sensitivity) from the oil potentially spilled (and where affected areas are determined by oil spill modelling). Further details are comprehensively described in chapter V.

Nevertheless, a hazard-based risk analysis is also performed in this work, when studying the drift of remote-based detected oil spills in the Portuguese coast – in this case, coastal sensitivity is not considered, neither likelihood of having a spill. Full details are available in chapter IV.1.

III Developing spill trajectory and weathering modelling for operational purposes

III.1 Overview

This chapter presents the published research work and efforts done to test, integrate and apply the developed oil spill model (fully described in chapter II.2 and Annex 1) in operational contexts and in multiple decision support tools. These efforts started with a review of the state-of-the-art in terms of available operational on-demand oil spill modelling systems across the world, in terms of their features and functionalities. The final result achieved demonstrates a consolidated oil spill modelling system not only capable of responding to the usual on-demand forecasting capacities available worldwide, but also a novel flexible model framework that is easily applied in multiple geographical scales, transferable, and potentially suitable for different purposes in terms of multiple risk management approaches, which are then further detailed and explored in subsequent chapters (IV and V).

III.2 Integration of an Oil and Inert Spill Model in a Framework for Risk Management of Spills at Sea – A Case Study for the Atlantic Area

Abstract

The integration of multiple information layers from different regions in a common framework is particularly relevant when dealing with interregional and transnational pollution problems, very common in the Atlantic area. An integrated framework for the support of modeling fate and behaviour of oil and inert spills was designed in EASYCO, ARCOPOL and ARCOPOL+ EU research projects, where various metocean forecasting systems from different institutions were integrated in a common polycentric approach.

This paper describes recent updates of the oil and inert spill modeling component of MOHID model, including interfacing with EASYCO metocean data and the integration with novel Decision Support Systems (DSS) also presented here. MOHID updates include: a) an innovative multi-solution approach to dynamically integrate available information from multiple metocean forecasting solutions available for each model simulation; b) a new approach for the simulation of drifting buoys with subsurface drogues and floating containers; c) backtracking modeling; d) coupling to wave models and inclusion of Stokes drift; e) vertical movement of entrained oil; f) review of oil weathering processes including a new approach for emulsification.

Several case studies highlight the new capabilities of the MOHID model and the implemented DSS. Developments show increasing versatility for application in a wider range of situations, including improved simulation of drifting buoys or pollution source tracking. The multi-solution feature, included in particle transport module, also increases versatility when dealing with different metocean data sources with different scales. This is especially useful when processes studied (like marine pollution) can assume an interregional or transnational dimension – like the EU Atlantic Area. The DSS also show strong potential to be used in different areas and applications.

III.2.1 Introduction and Background

The increasing predictive capacity of environmental conditions and fate or behaviour of pollutants spilt at sea or costal zones combined with monitoring tools (e.g. vessel traffic control systems) can provide more robust support for decision-making in emergency or planning issues associated to pollution risk management.

Over the last few years, a new generation of different oil and inert spill decision-support systems (herein referred to as DSS) is being designed and developed by government agencies and private industry, aiming to provide a more detailed and realistic support to the prevention and response teams. When compared with the old generation systems, these were either too simplistic or too complex and slow.

This new generation of DSS is now pushing monitoring and modeling efforts forward, creating synergies that provide mutual benefits for the creation of innovative software technology, and also for the stimulation of research and development around modeling and monitoring activities.

In the early 90's, one of the most relevant DSS became popular due to its simplicity, speed (very fast), availability (publicly available), and extensive oil products database – ADIOS (NOAA, 1994). This software has been continuously updated, and ADIOS 2 was released in 2000 (Lehr et al., 2002). Even today, ADIOS (2) is widely used as an extensive oil products library and as a first test of the expected behaviour of the oil. It is also used as a reference weathering model, being compared with other new models, when ground-truth weathering data is not available (Berry et al., 2012). However, ADIOS does not simulate oil spill trajectory.

Meanwhile, other DSS started to be developed in order to provide a more accurate and detailed analysis and prognosis, often including a graphical user interface with typical GIS support. Several examples of these tools became commonly used around the world by private oil companies, consulting engineering firms, research institutions and government agencies. GNOME (although this one with limited weathering processes) (Beegle-Krause, 2001), SLROSM (Belore, year unknown), OILMAP (ASA, 1997; ASA, 2004), OSCAR (Reed et al., 1995a; Reed et al., 1995b; Aamo et al., 1997; Reed at al., 2001), OSIS, GULFSPILL (Al-Rabeh et al., 2000), or MOHID (which is used and developed in this work; Fernandes, 2001; Janeiro et al., 2008; Mateus et al., 2008; Leitão et al., 2013) are some relevant examples. At this stage, the inclusion of variable metocean / environmental data as input for oil weathering tools started to be possible for the end-user, although these data should be pre-formatted and manually added to the system. These tools are very relevant on planning stages and studying different spill scenarios, since different sets of metocean conditions can be imposed to the models.

Recent operational oceanography and meteorology and the advances in terms of computational technologies lead to the development of new desktop or web-based operational products, capable of automatically and seamlessly integrating data sets from forecasting systems. Among them are MOTHY (Daniel, 1996; Daniel et al., 2003), OILMAP evolution + OILMAPWEB + SARMAP, POSEIDON OSM (Pollani et al., 2001; Nittis, 2006), MEDSLICK (Zodiatis et al., 2012) / MEDSLICK II (De Dominicis, 2013 – part one and part two), Met.no's OD3D (Hackett et al., 2006) + LEEWAY (Breivik et al., 2008; Breivik et al., 2012), OILTRANS (Berry et al., 2012), BSHmod.L (Broström, 2011), SEATRACK Web (Ambjorn et al., 2011). These tools are in general non-commercial solutions, mainly used and maintained at an operational basis, by prevention and response authorities. Moreover, most of these tools were created to specifically answer the questions raised by those end users and, therefore, focused in well-defined geographical areas. They are also limited to the use of a small number of operational solutions (often only one) for each needed metocean property. An exception is the ASA's commercial products - OILMAP / OILMAPWeb / SARMAP, which can be coupled to a large set of operational forecasts from several different data providers, through their aggregated environmental data solution server - *EDS*.

A synthesis of the processes modeled in the systems mentioned above is presented in Table 1.

Table 1 - Processes presently modeled by examples of referenced oil or inert drift modeling systems

	ADIOS	GNOME	OILMAP / SARMAP /	OSCAR	MOTHY	POSEIDON OSM	MEDSLIK	MEDSLIK II	SEATRACK WEB	OILTRANS	BSHmod.L	SLROSM	OD3D + LEEWAY	GulfSpill	MOHID
Advection	-	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Diffusion	-	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Wind drift	-	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Stokes drift	-	-	-	+	+	+	-	+	+	+	+	-	+	-	+
Floating objects	-	-	+	-	+	-	+	+	+	-	+	-	+	-	+
Backtracking	-	-	+	-	+	-	+	-	+	-	-	-	-	-	+
Stranding	-	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Spreading	+	-	+	+	+	+	-	-	+	+	+	+	-	+	+
Evaporation	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Emulsification	+	-	+	+	+	+	+	+	+	+	+	+	+	+	+

Natural Dispersion	+	-	+	+	+	+	+	+	+	+	+	+	+	+	+
Vertical Movement	-	-	+	+	+	+	-	-	+	-	+		+	-	+
Dissolution	-	-	+	+	-	-	-	-	-	-	-	-	-	-	+
Sedimentation	-	-	-	+	+	+	+	+	+	-	+	-	-	-	+
	ADIOS	GNOME	OILMAP / SARMAP /	OSCAR	MOTHY	POSEIDON OSM	MEDSLIK	MEDSLIK II	SEATRACK WEB	OILTRANS	BSHmod.L	SLROSM	OD3D + LEEWAY	GulfSpill	MOHID

(Note: the information sources for this table were mainly obtained from the references and bibliography cited in this paper; MOHID already includes developed processes described in this paper)

Summarizing, this wide panoply of DSS seems to give a positive answer to many different end users involved, operating with user-friendly interfaces, providing GIS outputs from model results, and most of them (with a few exceptions) making use of state-of-the-art equations and processes for the simulation of oil and inert trajectory and behaviour. However, some of them are not prepared or have a limited capacity to backtracking mode or to include wave-induced transport (Stokes Drift). Furthermore, some of them are not able to reproduce the vertical movement of oil droplets or to make use of 3d hydrodynamic fields (usually using only one layer, either the surface or an integration of the water column). Also, none of them have the possibility of integrating different metocean forecasts for different regions in the same simulation. This issue can become more relevant when managing potential transnational or interregional accidental pollution spills. Additionally, recent advances and massification in operational oceanography and meteorology forecasting systems are generating many metocean solutions at different scales, from the global scale till the very high resolution level.

DSS and numerical models for the assessment of accidental pollution should be able to take advantage of the different solutions provided without being constrained to one solution per simulation, or using only one vertical layer for hydrodynamics and water properties. They should also allow backtracking mode, which is in general a powerful tool helping to track spill origins.

In the present work, an integrated framework of DSS properly supported by an adapted MOHID oil and inert drift component has been implemented, in order to reduce the main gaps mentioned above.

III.2.2 Methods

III.2.2.1 Integrative framework for Risk Management: The EASYCO-polycentric Approach / Environmental Conditions

The high heterogeneity of operational systems available in the Atlantic zone, with strong overlapping of several different forecasting systems, and focusing on various types of solutions, models, scales, and areas, can be seen as a potential problem to emergency response or risk management tools, due to the large amount of information available in critical management systems, as discussed in this paper. However, it can also be seen as a good opportunity to take advantage of the different operational systems, usually focused and validated on specific spatial scales and zones with different resolutions (from local to global scales), integrating and promoting the harmonization of those model results.

The proposed approach was the development of a harmonized polycentric solution, where any or many of the model results can be visualized, and also used as environmental data in the oil & inert drift modeling system (herein referred to as OIDM). This polycentric approach can then easily facilitate intercomparison exercises, boost the development of common interfaces or web software systems, as well as improve efficiency in response activities for management of transnational and interregional pollution episodes.

Two different solutions can be adopted for dealing with all these data layers: using a centralized server (automatically downloading metocean model results to a central server, which then will be able to feed different DSS) or a distributed approach (DSS will use directly the metocean model results from the multiple data providers).

Several inconveniences were found in a distributed approach. If oil and inert drift simulations have to be executed in a matter of seconds, the process of downloading and interpolating metocean data from remote servers on-the-fly can be unstable. Moreover, most of the oil spills can have a significant variation due to vertical movement (entrainment / sinking / rising). Therefore, all of the 3D layers from hydrodynamic model results should be defined as possible input. This increases substantially the amount of information being used by the OIDM, reducing the possibility of downloading information on-the-fly.

In relation to a centralized server, the main disadvantages can be found in the creation of an additional data layer, instead of directly using outputs from the data provider. The other disadvantage is the storage of a high volume of information. Since the proposed approach was mainly to deal with prevention and response to emergency situations of accidents at sea, the storage of historic data can be discarded. Also fast 3D simulations were required, and accessing distributed remote servers for acquiring metocean data during the simulation process could become a bottleneck.

Based on these requirements, the centralized server was implemented and tested.

EASYCO data server automatically downloads and converts multiple metocean data sources (Download & Conversion Service) to be ingested by the different DSS developed and the OIDM as well, indexes those files (using Apache Lucene), stores these results on the server during a period of 15 days, then it is able to provide multiple remote downloads of these files upon request (EASYCO Data Service); lastly, MOHID Web Service runs the OIDM by request.

Although the Download Service is able to be configured and adapted to different types of data sources and services (OPENDAP, FTP, HTTP), a common EASYCO methodology was proposed for model output files in order to facilitate exchange of information between partners and the integration with downstream services, as the DSS. The common methodology proposed was based on netcdf file and takes CF conventions (Eaton et al., 2011) as a standard. The recommended method for publishing model data to be used by EASYCO server was THREDDS data server.

Mohid Web Model Service was developed to perform automatic particle tracking model runs with MOHID OIDM, based on a submitted xml string or a query string with a list of origin locations, and returning a xml string with MOHID data grid results.

The generated EASYCO data service is available online and can be used to feed different software applications (local or remote), such as Web GIS visualization systems, or DSS as described in the next chapters.

MOHID Web Service can also be automatically requested by different software tools.

III.2.2.2 DSS Developed

Different type of model-based software applications was developed, in order to show the versatility of the polycentric approach being tested, and also forcing MOHID OIDM to be adapted to fulfill the needs of those applications.

All the tools developed were mainly prototypes and demonstration tools for short-term accident pollution prevention and response activities.

EASYCO WBT

The EASYCO Web Bidirectional tool consists in a demonstration website built in a WebGIS environment that provides metocean results from the different operational systems, allowing:

a) to visualize metocean forecasts at different vertical layers;
b) to simulate on-demand inert and oil spills in a matter of seconds
c) to simulate on-demand displacement of Harmful Algal Blooms as well

On-demand simulations run in server (with MOHID), and results are displayed on the website after a few seconds, depending on the number of lagrangian particles used. The on-demand simulations can use constant user-defined values for environmental parameters, or a group of available metocean solutions selected and sorted by the end-user. Model results and simulations are available in a 15-day history.

The information displayed to the user is read by the web interface as a WMS client, and can also be exported to an external WMS server, increasing the interoperability of the system.

ARCOPOL Offline Spill Simulator

The ARCOPOL (CETMAR, 2013) Offline Spill Simulator (herein referred to as OSS) was designed to work in a desktop / laptop environment, in order to give more detail, options, interoperability (like exporting spill results to kml - Google Earth format or ESRI shapefile) and stability for simulation and results visualization, compared to the web-based interface. The idea behind this concept was to demonstrate the possibility of creation and design of an advanced and fast simulation tool, using best available metocean solutions for the Atlantic zone (supplied by EASYCO data service). Hence, main purpose was to run oil & inert spill simulations in MOHID disconnected from the internet, in order to increase the operationality during crisis or situations of imminent risk. Spill simulations can also be executed considering only constant metocean data conditions (instead of using space and time varying data). An exhaustive database of oil products was included, based on ADIOS 2 internal database.

A model download service was implemented and configured, in order to select and schedule the automatic downloading of metocean model solution(s) needed and defined by the end-user.

This tool can also be used as a visualization tool of the downloaded metocean model results.

Dynamic Risk Tool

This system provides:

a) coastal pollution risk levels associated to potential (or real) oil
b) spill incidents, taking into account regional statistics information on vessel accidents history and coastal vulnerability indexes (Environmental Sensitivity Index and Socio-Economic Index, determined in EROCIPS project),
c) real time vessel information (positioning, cargo type, speed and vessel type) obtained from AIS, best-available metocean numerical forecasts (hydrodynamics, meteorology - including visibility, wave conditions) and
d) simulated scenarios by the oil spill fate and behaviour component of MOHID Water Modeling System (here referred to as MOHID OIDM).

Different spill fate and behaviour simulations are continuously generated and processed in background (assuming hypothetical spills from vessels), based on variable vessel information, and metocean conditions, and results from these simulations are used in the quantification the consequences of potential spills.

This system was initially implemented in Portugal as a prototype.

III.2.2.3 Oil and Inert Spill Modelling System

The different DSS implemented in this study are supported by an OIDM capable of simulating the trajectory & behaviour of oil pollutants, drifting buoys, or floating containers. This model is a component of MOHID Water Modeling System (Instituto Superior Técnico, 2013; Neves, 2013), integrated on MOHID lagrangian transport module, with simulated pollutants or objects represented by a cloud of discrete particles (or super-particles) advected by wind, currents and waves, and spread due to random turbulent diffusion or oil mechanical spreading. The super-particles also contain information about the oil rheological properties (density, viscosity) and main weathering processes (spreading, evaporation, emulsification, natural dispersion, sedimentation, dissolution) (Mateus et al., 2008).

This model has the ability to run integrated with hydrodynamic solution, or independently (coupled offline to metocean models), being this last one the option for the developed operational tools (to reduce computation time, taking advantage of metocean models previously run).

MOHID lagrangian module has been widely used in different types of studies and applications, not only in oil spills, but also in sediments transport, harmful algal blooms (Mateus et al., 2012), fish larvae (Nogueira et al., 2012), residence time in estuaries (Braunschweig et al., 2003), faecal contamination in bathing waters and plume diffusion and dispersion (near and far field) in water column from submarine outfalls or rivers (Miranda et al., 1999; Viegas et al., 2009; Viegas et al., 2012).

This integrated OIDM was initially developed and implemented in 2001 (Fernandes, 2001), and in the last years it has been successfully applied and validated in different applications (Balseiro et al., 2003; Carracedo et al., 2006; Janeiro et al., 2008; Mateus et al., 2008; Pierini et al., 2008; Fernandes et al., 2012). Oil spill simulations have been used since *Prestige* Oil Spill (2002), where oil spill trajectory forecasts were effectively generated, having successful results. Forecasts were generated in the early stages of the oil spill, and predictions were initially validated in-situ by the response team, afterwards, by remote sensing, and at last, by aerial observations. Since then, MOHID has been used operationally in other real accidents and in spill exercises performed by Portugal and Spain, always generating satisfactory results.

During the execution of this work, MOHID OIDM was also updated and applied in the simulation of deep water blow out of oil spills (Leitão et al., 2013).

Updates in MOHID Oil & Inert Drift Model

The updates in processes and features performed during the execution of this study were needed to fulfill the final purpose of building modeling software capable of responding to the high demands proposed for the development of an innovative and complete risk management infrastructure for spill incidents, composed by the previously referred DSS being developed.

- **Backtracking Mode**

This feature allows performing model simulations of the trajectory of particles, running backwards (advection and diffusion processes are both included, but oil weathering properties are not simulated in backtracking mode). This means the model is now able to simulate possible sources or past trajectories based on an actual oil slick / inert object position, which is an added value in emergency response activities, or in the identification and tracking of potential pollution sources (e.g., vessels responsible for illegal discharges).

- **"Multi-solution" Approach**

In the scope of the EASYCO project's predecessor (EASY project), MOHID lagrangian transport module started to be updated to include a multi-mesh functionality, allowing particles to move along different model domains / grids. The main advantage on this approach is the possibility of take use of high resolution models when and where available. Advantages of this functionality become even clearer when studying oil or inert drift incidents in interregional or transnational areas (very common in Atlantic Area, e.g. *Prestige* accident), where several different metocean model results are available in different regions. In these cases, the integrated use of metocean model results can become an advantage, increasing the coverage of the whole area. Other application for this multi-solution approach implemented in lagrangian module is the simulation of water quality (coliform bacteria) involving nested models for bathing waters, where usually a very high resolution grid (dx = 30m) is needed (Viegas et al., 2012). The approach gives the possibility of transporting the modeled lagrangian properties along the different nested models, instead of being confined to a single nested domain (which usually covers a small area). The execution of this feature implied an integrated grid interpolation for the whole domains used at the beginning of the simulation.

During EASYCO project, this feature has been improved and optimized, in order to increase operationality and execution performance. Hence, MOHID lagrangian module was updated to compute the needed interpolations on-the-fly, and limit these interpolations to a specific spatial area where lagrangian particles are present (instead of interpolating wide spatial domains).

This new development was rather important to the execution of the initial idea behind the polycentric modeling framework, in order to take advantage of several different operational modeling systems, and use them in an integrated way, feeding the different

DSS already presented, and allowing the execution of the internal OIDM in a very short period of time (in a matter of seconds).

- **Floating Containers**

A drift modeling of inert cargo containers was implemented on MOHID modeling system. The approach derives from the analytical solution of the basic movement conservation equation, as proposed by Daniel et al. (2002):

$$m\frac{\partial \vec{V}}{\partial t} + mf\vec{k}\Lambda\vec{V} = \vec{F}_a + \vec{F}_w + \vec{F}_r \tag{1}$$

t denotes time, m the mass of container, V the horizontal velocity of the container, f the Coriolis parameter, k a unit vector in the vertical, F_a the wind drag, F_w the water drag, and F_r the wave radiation force.

Model only considers containers that do not sink, and assumes that containers are flat in the water and aligned with the wind.

Assuming a steady state, and neglecting the Coriolis parameter and wave radiation force, in the end MOHID computes the container's velocity from the analytical solution of previous equation, as implemented on a model developed by Météo-France (Daniel et al. 2002), but without assuming null water current (which means that the physics of the container simulated by MOHID takes into account the hydrodynamics on the submerged part, and the wind action on the emerged surface):

$$\rho_a C_a (100 - I)\left|\overrightarrow{V_a} - \vec{V}\right|(\overrightarrow{V_a} - \vec{V}) + \rho_w C_w I\left|\overrightarrow{V_w} - \vec{V}\right|\left(\overrightarrow{Vw} - \vec{V}\right) = 0 \tag{2}$$

where ρ_a is the air density, C_a is the drag coefficient, V_a is the wind velocity. ρ_w is the water density, C_w is a drag coefficient, and V_w the water velocity. The end-user only has to define the immersion rate, water drag coefficient and air coefficient rate. These coefficients are based on experimental work (Daniel et al, 2002).

- **Drifting Buoys with Subsurface Drogues**

MOHID lagrangian transport module was only prepared to simulate the behaviour of standard floating substances or substances that move in the water column based on density differences between the substance and the surrounding ambient (water). In order to simulate the movement of the drifting buoys with underwater / subsurface drogues more realistically, lagrangian module was updated, being now possible to define in MOHID a constant depth (which should be the depth of the drogue) relatively to the free surface, and simultaneously include a wind drag coefficient, which will be applied at the corresponding surface. Thus, MOHID is now able to simulate the transport of tracers / buoys influenced by the currents at a constant depth relatively to the free surface, and by a wind drag force applied at the surface. This update allows studying the trajectory of several types of buoys deployed around the world, which usually have drogues associated, in order to study the currents at specific depths. The referred feature can then be useful to better validate hydrodynamic models based on buoys trajectories coming from different sources, like ARGOS buoys.

- **Coupling to Wave Models and Horizontal Velocity due to Stokes Drift**

The coupling with wave models is relevant since some oil weathering processes can depend directly from wave properties (e.g. vertical entrainment / natural dispersion). Hence, "offline" coupling of MOHID lagrangian model with wave model results were made possible, using wave height, wave period, wave direction, or even wavelength. Following this, the Stokes drift component was also included in the modeling system. Stokes drift velocity (or mass transport velocity) is the average velocity of a particle due to the orbital motions induced by waves (Stokes, 1847), in the direction of wave propagation. This velocity is calculated for each particle, and velocity components are then added to the horizontal velocities of the particle calculated in MOHID.

The determination of the Stokes drift velocity (u_s, in m/s) in MOHID is mathematically represented as (Daniel, 2003; Longuet-Higgins, 1953):

$$u_s = a^2 \cdot \omega \cdot k \, \frac{\cosh\left[2 \cdot k (z-h)\right]}{2 \cdot \sinh^2 (k \cdot h)} + C \qquad (3)$$

Where h (m) is the water depth, z (m) is the depth below surface, a (m) is the wave amplitude ($a = H / 2$), □ (rad/s) is the wave circular frequency ($\omega = 2\pi / T$) and k (m^{-1}) is the wave number ($k = 2\pi / L$) for waves with height H (m), period T (s) and wavelength L (m). C is a depth independent term:

$$C = -\frac{a^2 \cdot \omega \cdot \sinh(2 \cdot k \cdot h)}{4 \cdot h \cdot \sinh^2 (k \cdot h)} \qquad (4)$$

The wavelength can be read from a wave model output, or manually defined by end user. Otherwise, MOHID internally calculates wavelength based on an explicit approximation of the wave dispersion equation, proposed by Hunt's method (Hunt, 1979).

The direction of the Stokes' drift is set equal to the local wave direction. If wave parameters H and T are not available from a wave model, they can be defined by the end-user, or calculated inside MOHID, using simplified internal models based on wind, previously implemented.

- **Vertical Movement of Entrained Oil**

Although a major number of oil spills take place at the surface, after the accidents the oil can be pushed down into the water column by the energy of breaking waves. Since its implementation, MOHID OIDM is able to compute the entrainment rate using Mackay, 1980 approach, or the classic method from Delvigne and Sweeney, 1988.

If the oil penetrates the water column after a surface spill, this means that oil will be subject to a vertical velocity, depending on the density differences and oil droplets diameter. The correct modeling of these processes forces the implementation of a three-dimensional modeling approach.

The first process to model is the entrainment of an oil tracer in the water column, which will be based on a random procedure. The probability of a tracer being entrained in the water column due to breaking waves is obtained from the instantaneous model "entrainment deficit" - difference between the theoretical fraction of dispersed oil estimated by one of the dispersion formulas previously implemented in MOHID, and the global mass fraction of entrained oil particles. Thus, the probability of a tracer entraining the water column is greater when the entrainment deficit is greater, i.e., when the difference between the global dispersion fractions obtained by the theoretical equations and the mass fraction of oil droplets in the water column is greater.

Once a particle is on the water column, the second process to compute is the specific depth position. The particle's depth is randomly determined between surface and the intrusion depth $D_i = 1.5\ H_b$. (D_i is the intrusion depth, and H_b is the breaking wave height) (Tkalich and Chan, 2002).

The next step is to decide the droplet diameter associated to the particle. Ideally, each surface particle entrained in the water column should then generate new entrained particles with different diameters following a droplet size distribution (Delvigne and Sweeney, 1988). For computational reasons, the surface particle, once in the water column, has only one diameter. One of three different methods can be chosen by the user for the determination of droplet diameter:

a) each particle is assumed to have a typical user-defined diameter (default option = 0.05 mm, as proposed by Delvigne and Sweeney, 1988);
b) each particle is assumed to have a constant diameter equal to half of the mass median droplet diameter (d_{50}) (as proposed by Spaulding et al., 1992a)
c) a diameter is randomly assigned to each submerged particle based in the droplet size distribution profile. Five different droplet size classes equally spaced between a minimum and maximum droplet size are considered. Corresponding entrainment rates are then determined as proposed by Delvigne and Sweeney, 1988. In this approach, droplet sizes that tend to resurface in a short period of time, usually greater than the maximum droplet diameter (assumed to be d_{50}) are not considered. Also droplets below minimum droplet diameter (assumed as 10% of the diameter d_{50}) are neglected due to relatively small size.

Mass-median diameter can be determined as follows:

$$d_{50} = 1818\, E^{-0.5}\, (\mu/\rho_o)^{0.34} \tag{5}$$

Where E is the energy's dissipation rate per unit volume (J/m^3·s) (according to Delvigne and colleagues values are between 10^3 and 10^4). A value of 5000 was adopted. μ is the viscosity (mPa/s), and ρ_0 is the density of the oil (g/cm^3).

With this approach, at a given moment, an entrained particle will have a larger tendency to belong to a droplet size class with a higher entrainment rate.

The last step is the computation of the droplet buoyancy. The rising velocity will be based on the assumption that oil particles can be represented as spheres of given diameter and density. Thus, buoyancy velocity w_s will depend on density differences, droplet diameter d and water kinematic viscosity ν, as well as critical diameter d_{crit} (Soares dos Santos and Daniel, 2000).

$$d_{crit} = \alpha \frac{\nu^{2/3}}{|g'|^{1/3}}, \tag{6}$$

where g' is the reduced gravity (buoyancy)

$$g' = g\left(1 - \frac{\rho_P}{\rho}\right). \tag{7}$$

If the particle's diameter is greater than d_{crit} then

$$w_s = \frac{g'}{|g'|}\sqrt{\beta\, d|g'|} \tag{8}$$

Else

$$w_s = \frac{g'}{|g'|}\left(\frac{d^2|g'|}{18\nu}\right). \tag{9}$$

The values for □ and □ defined by default are 9.52 and 8/3, respectively, as proposed by (Soares dos Santos and Daniel, 2000). However, □ is probably too large, overestimating buoyancy velocity for larger diameters (Zheng and Yapa, 2000). Thus, a value of 0.711^2 can optionally be used for □, and since parameter □ is directly obtained by solving equations (8) and (9) for *d*, in this case, a value of 5.47 is used for □ (Liungman and Mattsson, 2011). In addition to this two-equation approach, a new integrated approach (Zheng and Yapa, 2000) considering three different regimes (small spherical droplets, intermediate ellipsoid bubbles and large spherical cap bubbles) is presently being included in MOHID.

The droplet buoyant velocity is then integrated with the vertical advection and diffusion components (the advected vertical velocity – from the hydrodynamic solution – and the vertical turbulent diffusion velocity component). This means that in waters with higher turbulence, the buoyant velocity becomes less important.

- **Review on Formulations of Weathering Processes**

Although the update and review on formulations for oil spreading and weathering processes in MOHID is still a work-in-progress, at the moment of the edition of this work, a new additional method has been included for the simulation of emulsification process. Emulsification is responsible for the incorporation of water droplets in oil, changing substantially the oil viscosity and therefore its behaviour at sea. In fact, after evaporation, emulsification can be considered the most important transformation process (Fingas, 2008). Emulsions had been studied extensively in the laboratory and field, thus many facets of their formation are now known, and the basics of water-in-oil emulsification are finally understood and well-established (Fingas and Fieldhouse, 2006; Sjöblom et al., 2003). The new method adopted in MOHID was proposed and detailed in Fingas, 2011, and already implemented in (Berry et al., 2012). The approach is based on the determination of stability class from extensive empirical data obtained in previous studies, and then related to an emulsion state (stable emulsion, meso-stable emulsion, entrained water and unstable mixture). The proposed model has the oil starting viscosity, its asphaltene and resin content and its density as the most mathematically relevant factors when determining stability class. This formulation is considered to be very much more accurate than the old methods (Fingas, 2011).

III.2.3 Applications and Results

In this section, different types of examples can demonstrate the capabilities of the updated MOHID OIDM, and also how this model, integrated with the developed polycentric framework, can improve the operational capacity in prevention and response strategies in the Atlantic zone.

III.2.3.1 Simulating Drifting Buoys in the Tagus Estuary Mouth

Drifting buoys were released in Estoril Coast. This is a mixture area within the Tagus estuary, with several stream discharges, small harbours and marinas, tide, ocean and river influence, generating specific hydrodynamic circulation patterns and providing different water quality and hydrodynamic fields along space and time (some of them can change in tide based regime) – see Figure 9 and Figure 10.

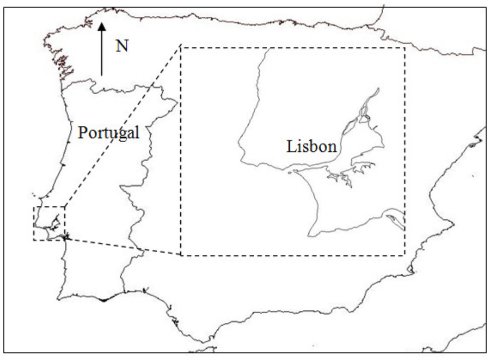


Figure 9 - Iberian Peninsula highlighting Tagus estuary location near Lisbon

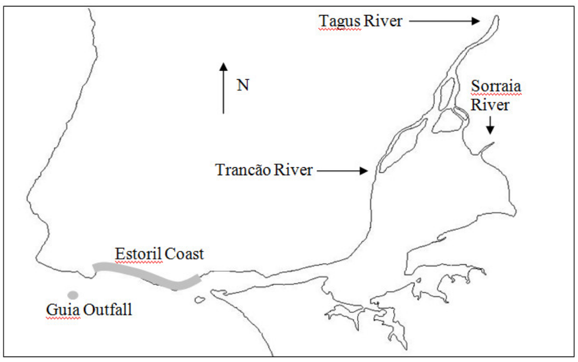


Figure 10 - Tagus estuary and the Estoril Coast

Due to its location and proximity to the open ocean waters, the water residence time in Estoril Coast can be considered small. Inside Tagus Estuary the residence time is in the order of one month, but in the case of the area of study (at the estuary mouth) it can be in an hourly scale and change with a tide cycle. Due to this short residence time in the area of study, surveys were done with a continuous in-situ monitoring, avoiding that buoys got overtaken on fish nets, or got out from the study area (to the Atlantic Ocean waters).

The metocean data used was available from other ongoing projects and research activities, where high resolution models were implemented and validated for that site (Viegas et. al., 2009; Viegas et al., 2012).

The drifting buoys used were MD02 surface drifters developed by ALBATROS Marine Technologies, Palma de Mallorca, Spain. They are small and security oriented buoys, having flexible closed cell PE foam buoyancy. Being a coastal buoy, its position is obtained by a GPS module, and it has a GSM data transmission system. In these field exercises, a drogue with different sizes was attached to the drifter. This drogue was kept underwater at a constant depth, depending on the size of the drogue. The purpose of this drogue was to reduce the direct influence of wind on the buoys trajectory (see Figure 11). Therefore, the application of a drogue minimizes the wind drag effect on the surface buoy.

Figure 11 - Drifting buoy with underwater drogue

The operational drift modeling system / OIDM was used as a tool to simulate and fit the modeled trajectories to the ground truth trajectories from experiments, and also to prepare and select release locations and time periods for buoys and dyes. Different scenarios and release points for each survey were simulated in a matter of seconds. During this model simulation analysis, it was possible to observe that small differences on time and local releases could have different results. A delay of 10 minutes or a deviation of one or two hundred meters from the planned point could be enough to produce a different behaviour of the buoys, which supports the idea of "Lagrangian chaos".

The influence of buoys configuration and ocean-meteorological conditions in the buoys trajectory were also tested. Several different drifting buoys were released under different meteorological and hydrodynamic conditions. Hence, the field work performed was used to model calibration and validation. In the experiments performed, an optimal wind drag coefficient between 1 and 2% was found (Figure 12).

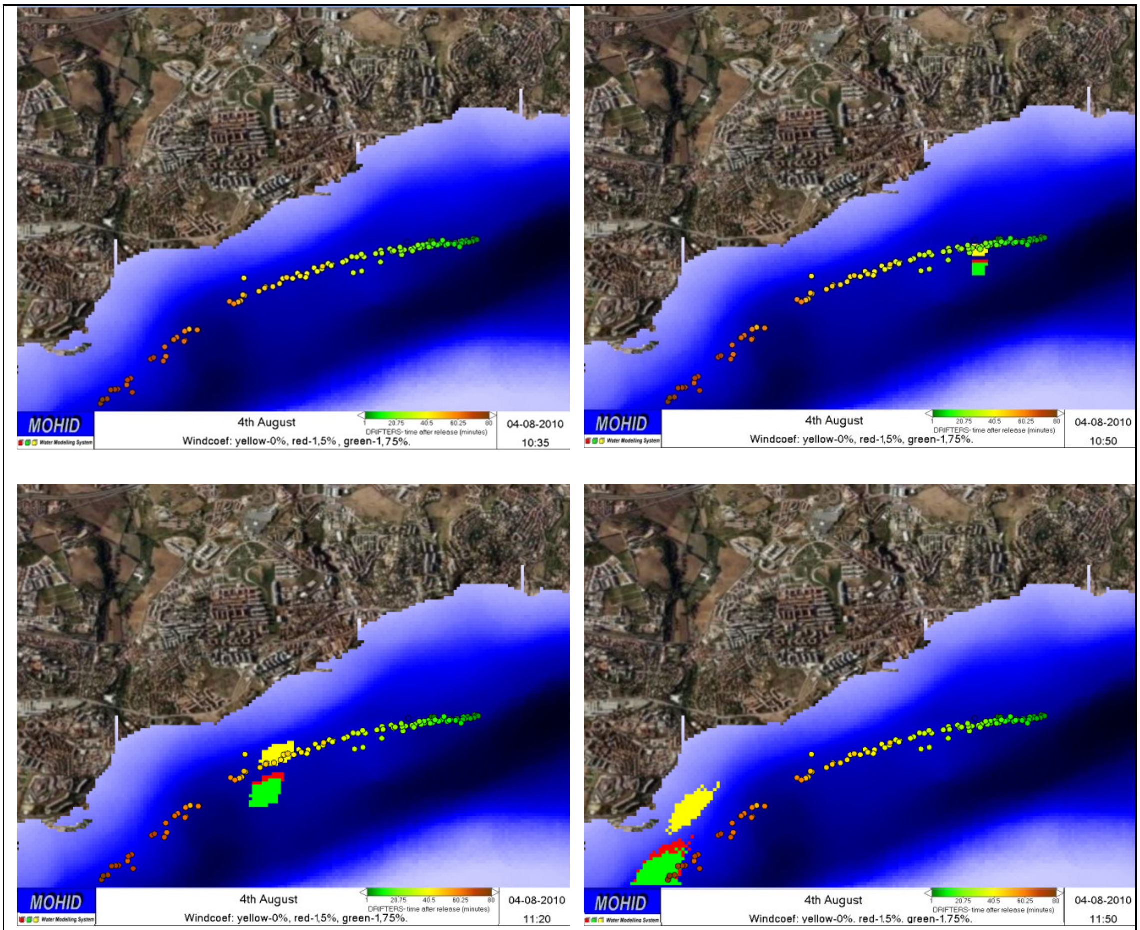


Figure 12 - Buoys survey, on 4th August 2010: measured data (buoys position represented by markers with color scale representing time after release – dark green is immediately after release) vs. MOHID drift simulations in 4 different instants, considering different wind drag coefficients: 0% (yellow polygons), 1.5% (red polygons), 1.75% (green polygons)

Data from 4th August survey were additionally used to test and compare backward and forward model runs against measured drifter data (Figure 13). As can be seen, both model runs present similar average positions, but they differ in particle "cloud" areas due to turbulent diffusion, increasing more in backtrack run, near the buoys release position (as a result of higher current velocities at this point). Initial and final positions of backward and forward model runs are coincident with measured data, although the trajectories have some differences.

Figure 13 - Buoys survey, on 4th August 2010: black dots - measured buoys position along time; red polygons – particles from backward model run; green semi-transparent polygons – particles from forward model run

Drift model results using atmospheric models with different spatial resolutions were also compared (Figure 14). Two different scenarios were analysed considering the two different atmospheric forecasting models available: MM5 (with a resolution of 9km), and WRF (with a resolution of 3km). Both atmospheric models are implemented by IST to the study case site. Significant differences were found between the two atmospheric models evaluated. Drift model results compared better with data using WRF – 3km, as expected.

Several other exercises were successfully performed in order to calibrate the particle turbulent diffusion based on the “spreading” of a number of drifters initially released at the same time and location.

Another interesting result was the validation of buoys under a water mass front episode (fresh water coming from Tagus river, and salt water from open sea). Buoys tend to drift along the front, explained by the differences in density between both water masses, generating a tidal convergence front which “traps” the buoys there – Figure 15.

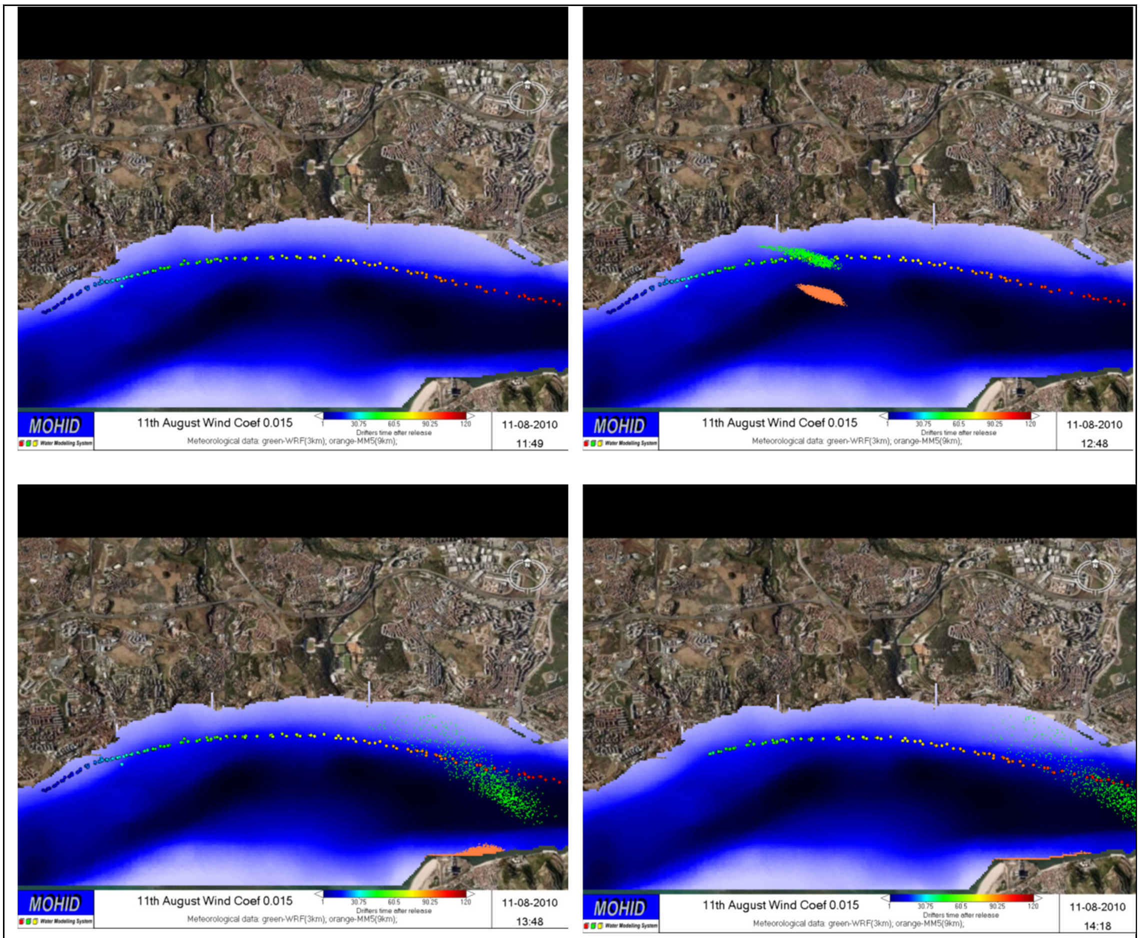


Figure 14 - Buoys survey, on 11th August 2010: measured data (buoys position represented by markers with color scale representing time after release – dark green is immediately after release) vs. MOHID drift simulations at 4 different instants, considering wind forcing: WRF (3km) in small green dots, MM5(9km) in small orange dots.

Figure 15 - Convergence of different water masses, recorded on 27-8-2010, with buoys "trapped" in the water-mass front

Since a local 3D hydrodynamic model was used to feed the drift model, it was possible to evaluate the ability of both models to reproduce this front. In terms of hydrodynamic modeling, results appear to simulate the front in agreement with the drifting buoys position (Figure 16). This was only possible due to the fact that this is a 3D fully baroclinic model, with a very high spatial resolution.

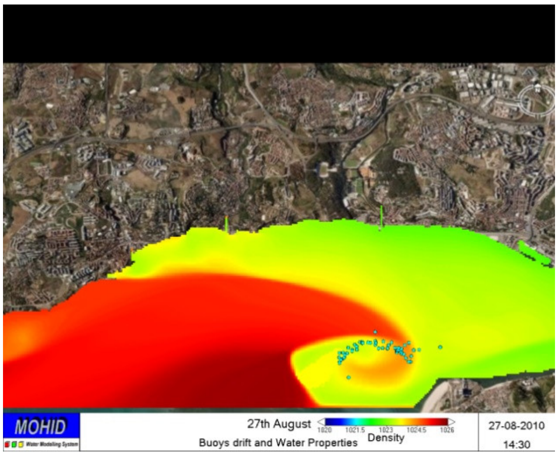


Figure 16 - Instant drifting buoys position and modeled water density during the front

In terms of drift modeling for this specific field experiment, results also showed a good agreement between observed and modeled trajectory (Figure 17). Modeled results were based on different particle turbulent diffusion velocity parameters (*VARVELHX*, as is called in MOHID, which is a water velocity multiplying dimensionless factor, in order to parameterize a correct standard deviation of the particle random movement velocity). At the beginning of the exercise the differences were small, but from the second hour on the difference became visible, and it was possible to see that larger diffusion lead to a larger simulated plume. For this survey, the value for turbulent diffusion parameter that better represented this behaviour is the 0.02 for *VARVELHX* (orange in image). However, 0.03 also seemed to be in good agreement with data, especially for the first moments. Greater values usually create an overestimated dispersion not observed in the developed surveys; smaller values produce a tracers “cloud” area too small to represent the variability of the drifter’s behaviour.

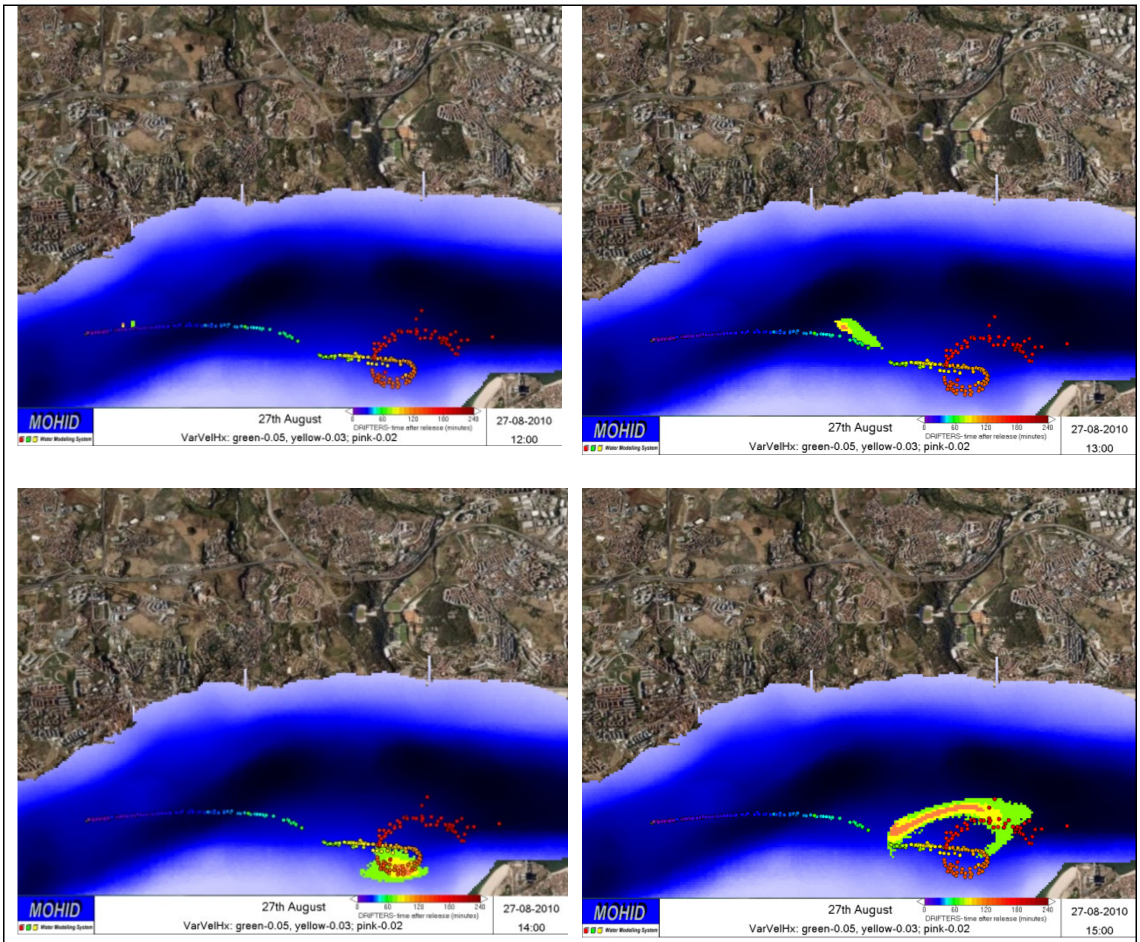


Figure 17 - Buoys survey on 27th August: measured data (buoys position represented by markers with color scale representing time after release – dark green is immediately after release) vs. MOHID drift simulations at 4 different instants considering different diffusion coefficient *VarVelHX*: 0.02 (orange polygons), 0.03 (yellow polygons), 0.05 (green polygons).

III.2.3.2 Oil Spill Exercise in Sesimbra (South of Portugal)

On 9th May 2012 a marine pollution response exercise "Xávega 2012" was held off Sesimbra, Portugal. The exercise was organised by the Portuguese National Maritime Authority (Autoridade Marítima Nacional-DGAM), with the aim of ensuring the measures in place - search and rescue, assistance for ships in distress, maritime pollution prevention. The scenario created was a ship-to-ship collision between two merchant vessels followed by a crude spill.

MOHID OIDM was applied in forecasting the scenarios considered, including a 500 m^3 oil spill (IFO 180). Different simulations were made, considering different wind drag parameters (Figure 18). Metocean data used was derived from the data sources made available at EASYCO data Service. In this case, different wind drag coefficients did not produce significant differences in model results, as modeled oil tracers seemed to appear almost in the same position. This was in fact explained by low wind (below 3 m/s) forecasted for this day, which was in fact confirmed during the exercise.

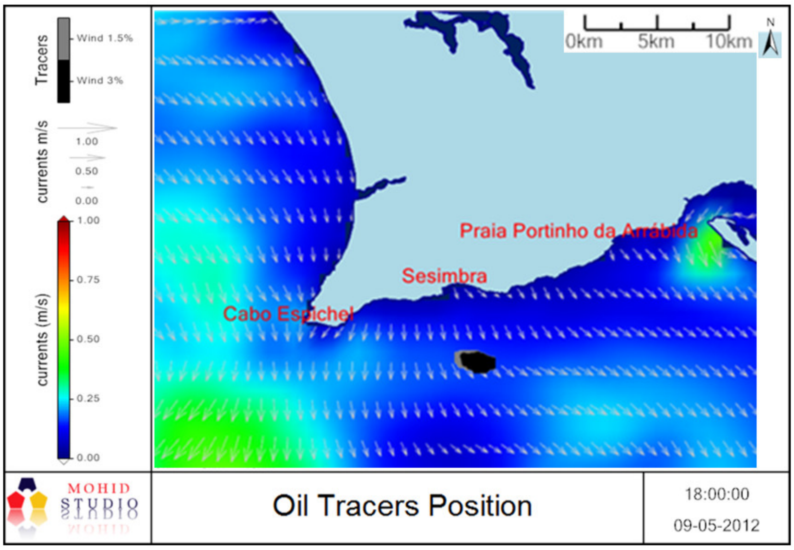


Figure 18 - Modeled oil tracers instant position: tracers with different wind drag coefficients showing similar positions (3% = black polygon; 1.5% = grey polygon)

III.2.3.3 Using MOHID Oil / Inert Spill Model Together With the Decision Support Systems

MOHID OIDM was effectively integrated in the different developed DSS. Most of the DSS became operational in 2012.

EASYCO web bidirectional tool was published in the project website (Instituto Superior Técnico, 2012a), and the EASYCO Data Service is now composed of several different data providers for the Atlantic Zone (Table 2 and Figure 19). Figure 19 shows a visual representation of sea surface temperature simulations from different data providers, studying different areas in different scales. A continuity in temperature can be seen in the different models, and the visual differentiation is possible due to different opacity levels for each model.

Table 2 - List of operational modeling data sources included in EASYCO data service

Institution	Model & Domain
IMI	ROMS – NE Atlantic
IMI	ROMS - Connemara
IMI	SWAN – NE Atlantic
IFREMER	MARS – Biscay Bay
Puertos del Estado	POLCOMS - Iberia
Meteogalicia	WRF – Galicia
Meteogalicia	WW3 - Iberia
Meteogalicia	WWE - Galicia
MERCATOR	OPA – N. Atlantic
NOAA	GFS - World

Institution	Model & Domain
IST	MOHID – Portuguese Coast
IST	WW3 - Portugal
	MOHID – Tagus Mouth
IST	MM5 – Portuguese Coast
IST	WRF – Tagus Mouth
IST	MOHID –Madeira
IST	WRF - Madeira
Azores Univ.	MOHID – Azores Central Group
Azores Univ.	MM5 - – Azores Archipelago
Azores Univ.	MM5 – Azores Central Group

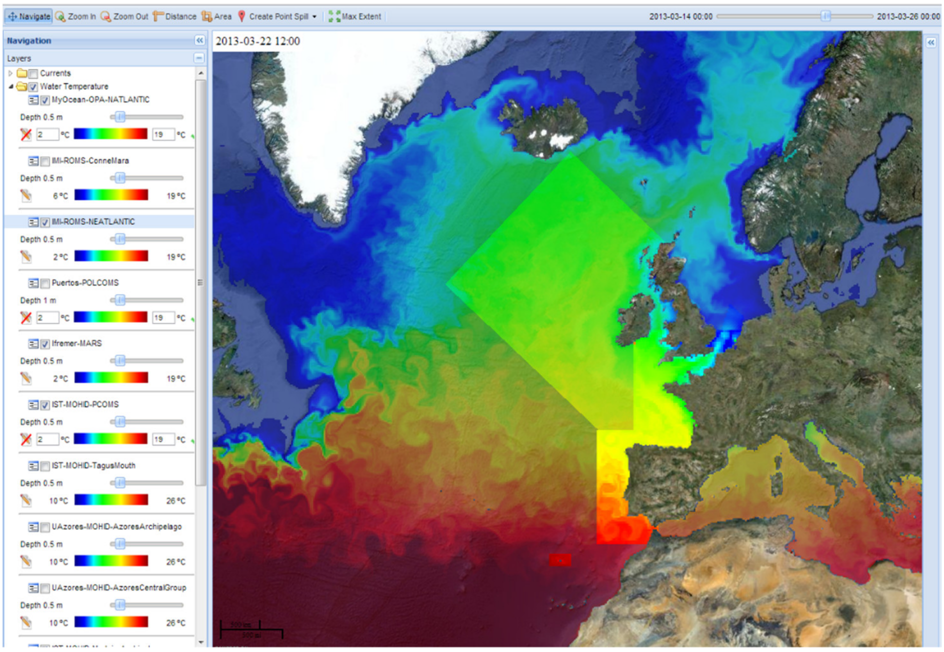


Figure 19 - Visualization of sea surface temperature of global and regional models from different data providers in EASYCO Web Bidirectional Tool. Same color scale is used, with different opacity levels.

The same methodology and web interface was applied with other metocean data remote services (and not only with EASYCO Data Service) and in other regions, namely the Brazilian coast – (Instituto Superior Técnico et. al, 2012b), in a joint effort promoted by IST, Hidromod and the Azores University. The web bidirectional tool has revealed to be a powerful integrative WebGIS tool to visualize and explore 3D model results.

In the first year of implementation (Table 3) specifically, between 9th February and 24th October 2012), in general, the success rate of the different procedures involving EASYCO server was reasonable, although the downstream procedures that were executed (as the generation of data, which feeds directly EASYCO WebGIS) usually had lower success rate, mainly because they depend on the success of prior processes. The high number of files and data sources processed in EASYCO server also increases the possibility of execution errors.

Table 3 - EASYCO Server performance for the different procedures involved, during 2012-02-09 and 2012-10-24

EASYCO Server Procedure	Performance
Server State	95%
Data Service State	81%
Execution of Download & Conversion	79%
Effective period with model data	72%
Generated data	52%

Server state failures (5%) were motivated by low disk space. Although the system has been developed to continue working even when upstream procedures have failed, if any execution fails when downloading, converting, or simply because data providers don't provide models when expected, effective period with model data is reduced, and then, consequently the generated data to supply WebGIS is even worse.

No monitoring activities have been reported in the Brazilian WebGIS application, but users have experienced much lower failure rate, mainly because server procedures are better isolated, with significantly less number of files and data sources to be managed.

In relation to OSS, this software was released to partners during ARCOPOL project, and presently software interface is being under updates and improvement in terms of new features, design and correction of bugs, under the scope of ARCOPOL PLUS project. This software is also using the developed MOHID OIDM and EASYCO data service. Apart from an initial testing stage where some problems were found in the download from internet connection to EASYCO Data Service, the system is now running stable. Meanwhile, it has been designed to allow connection to other metocean data remote web services as well. The most recent version of this software – now called Aquasafe Oil Spill Simulator (although is not limited to oil spills) – has been recently implemented by Hidromod in different regions, including an operational oil spill forecasting system for the Strait of Malacca, in the scope of a demonstration project promoted by IMO. Indeed, both DSS previously mentioned are now fully integrated in Aquasafe Platform (Hidromod, 2013; IWA, 2009).

This system is revealing a good stability (due to the fact that it is a desktop / laptop application) and strong performance in visualization and running MOHID OIDM (Figure 20). Since this software has advanced options in the visualization and analysis of results related to oil weathering processes and properties, as well as an exhaustive oil products database (based in ADIOS 2 internal database), this DSS has shown that it is well suited for technical and professional uses, like decision makers in oil spill prevention and response activities.

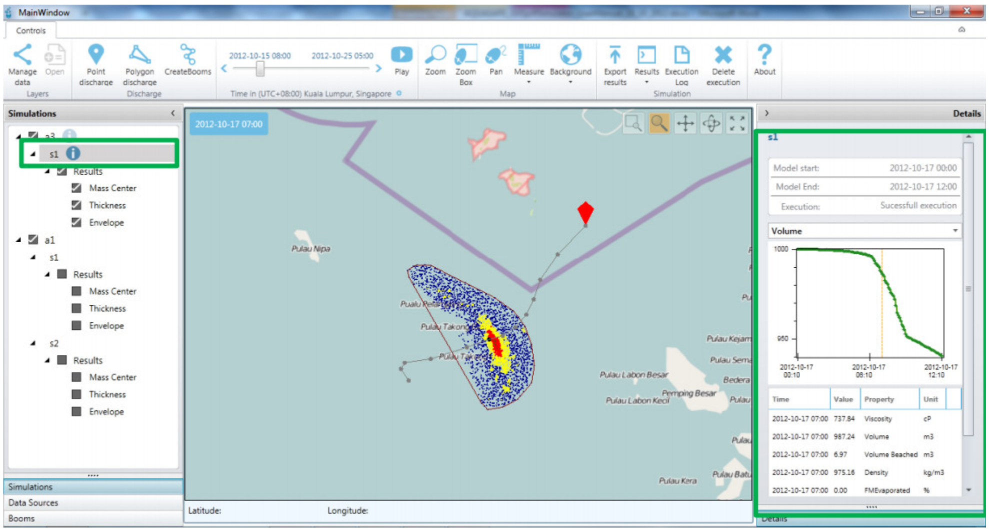


Figure 20 - OSS: example of displaying oil spill results –particles instant oil thickness (here displayed in a discrete color scale), instant slick envelope, center mass trajectory (in grey color) and oil weathering properties and processes evolution.

In relation to Dynamic Risk Tool implementation, this risk management tool was operationally applied as pilot project in the Portuguese Continental Coast, also making use of metocean data sources used in EASYCO data service. In this case, only one data source per environmental property is used. Presently, the application is configured to import data from IST's meteorological model in MM5, IST's wave model in WW3, and IST's Portuguese Coastal Operational System (PCOMS) in MOHID. Risk levels are generated in real-time, and the historic results are kept in a database, allowing later risk analysis or compilations for specific seasons or regions, in order to obtain typical risk maps (Figure 21).

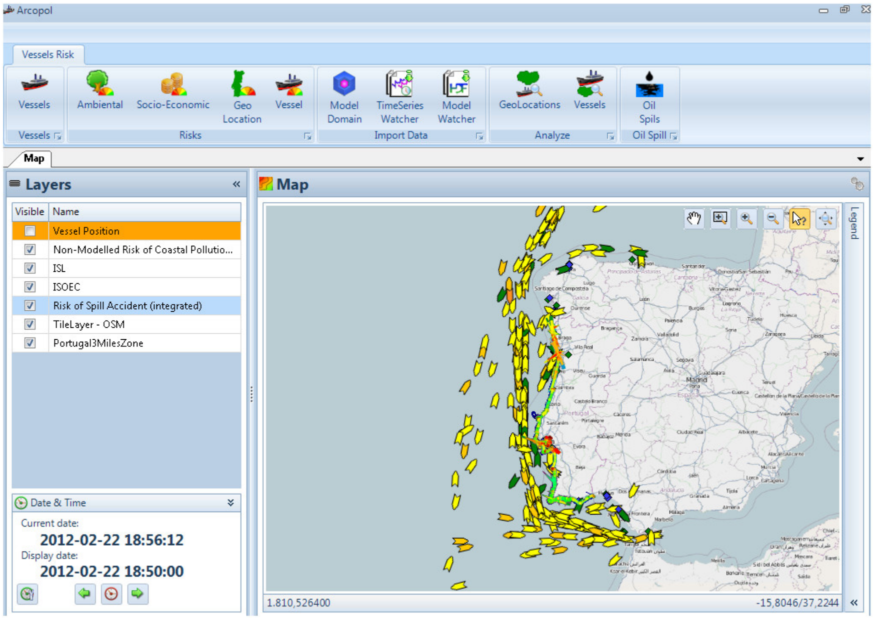


Figure 21 - Dynamic Risk Tool: Integrated Risk of Spill Accident represented in the vessels (green color = low risk; red color = high risk); Shoreline contamination risk represented by a line in the shore (green line = low risk; red line = high risk)

With the possibility of analyzing real time risks generated by a specific vessel, or finding the vessels posing higher risk to a specific site, this application can be used in the risk monitoring on a specific site (e.g. a port). This software can also be used to monitor and isolate risks coming from specific vessels (Figure 22).

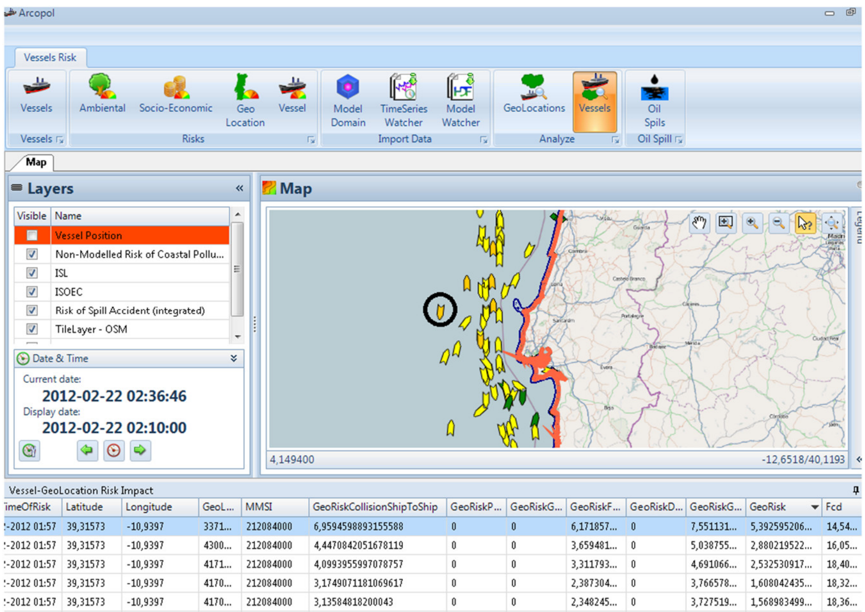


Figure 22 - Dynamic Risk Tool: Integrated Risk of Spill Accident represented in the vessels (green color = low risk; red color = high risk), and table representation of shoreline contamination risk values posed by one particular vessel selected.

Operational Support to Incidents

All the developments pursued in this work have been followed by Marine Pollution Response Service from Portuguese Maritime Authority (DGAM), where active cooperation has been helpful for a better understanding of their needs, or even finding eventual software limitations and improvements. During this cooperative approach, an incident came up on 6th March 2013, involving *Harbour Krystal* tanker. This vessel suffered a fire & explosion 13 miles off the Portuguese Coast, Southwest from Cape Espichel, when it was carrying 8000 tons of naphtha. After the incident, a crew member of the vessel was missing, although no spill was recorded.

Since this incident occurred in the area of implementation of the modeling infrastructure in the Atlantic, generation of spill forecasts in real time using OSS was possible, and results were exchanged with the Portuguese Maritime Authority. Simulated forecasts for a possible naphtha spill have shown approximation of the coast (although most of the product would rapidly evaporate and disperse in water column), should there be a spill (Figure 23). In a case like this, diverting the vessel to take shelter in a port of refuge can be a wise solution. Indeed, after technical inspections, Harbour Kristal received the authorization to take shelter at Setúbal Port on 7th March.

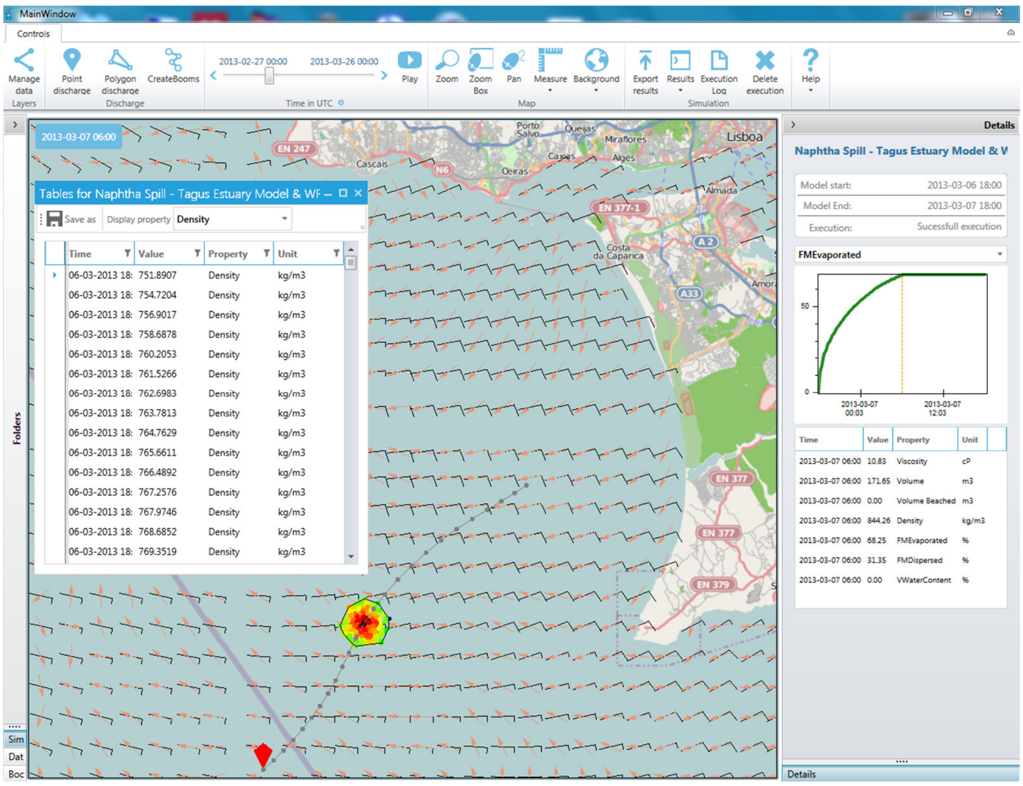


Figure 23 - Simulation of Harbour Krystal eventual spill (naphtha) using OSS.

Nevertheless, after the implementation of the developed system (since 2012), no data (aerial observations or satellite imagery) was obtained for possible validation of the tools implemented, in respect to the oil spill modeling system.

III.2.4 Discussion and Outlook

The approach followed in this work regarding the multi-solution feature in lagrangian particle transport module, has been tested in the different DSS. Its major advantages are related to the increase of versatility in MOHID particle tracking system when dealing with integrated metocean data with different scales (like nested models). This can be interesting in areas where several different metocean forecasting systems are available, and processes studied (like marine pollution) can assume an interregional or transnational dimension – like the EU Atlantic Area.

Since MOHID OIDM has been successfully integrated in several different operational DSS, some of the updates in model were already successfully tested in a few real situations and real time forecasts. Assessing these systems performance in real situations, is always desirable in order to verify their adaptability to new situations. Every incident always presents something new and unexpected in terms of modeling approach, putting existing models on test, and pushing forward research and development activities. Hindcasting and then showing accurate simulations for past incidents where final results are already known is sometimes the only possible way to properly validate a model, but the million dollar question is: will the modeling system be prepared for the next real accident?

During the *Prestige* accident, MOHID forecasted simulations were an example of real time "blind" validation, and where model adaptability and interoperability was put on test against ground truth data. However, some of the latest updates in MOHID presented in this paper require much more testing and validation when possible. This applies mainly to floating container modeling, and some oil processes, such as vertical movement of entrained droplets, or the new implemented emulsification algorithm. Active work is already in progress, regarding the calibration and validation of MOHID's hydrodynamic, turbulence and oil weathering processes, with specific exercises conducted in a meso-scale flume tank. Nevertheless, probably only real time forecasts of future incidents will be able to effectively check performance of MOHID OIDM as an operational modeling system supporting DSS.

The field exercises with drifting buoys highlighted the importance of using high-resolution and quality metocean modeling data as input to the oil and inert drift models. The same applies to atmospheric models: significant differences were shown in model simulations with different atmospheric forcing (MM5 9km vs. WRF 3KM), which was probably increased by the fact that the case study was near a complex urban area. Particles turbulent diffusion and influence of wind drag coefficient in model results were also studied, where low wind drag coefficients were found for the studied case (1-2%), probably due to a good vertical discretization in the surface layers, in the hydrodynamic model used. Backtracking feature was also tested and compared with field exercises, showing good agreement with forward running model.

The overall performance of the EASYCO Service has been positive, although experience has shown that it can be better in web servers with less workload (as the case of the Brazilian WebGIS application). EASYCO webserver has to download, convert, index and generate several different types of data sources. The way to avoid failures maintaining the same polycentric modeling infrastructure would be to improve server hardware performance, increase log and report automatic procedures, implement redundant services, or simply reducing the number of server procedures involved. This could be achieved if some of server procedures were distributed by local servers, or data providers.

OSS is revealing strong potential to be used in different areas and applications. This DSS was also tested in an emergency incident, where simulations were possible and timely exchanged with responsible maritime authorities. Integration of WebGIS application and OSS with Aquasafe platform will probably increase significantly the future number of end-users. Current developments integrated in ARCOPOL PLUS include the possibility of import satellite-detected oil slicks under EMSA's CleanSeaNet operational service (CleanSeaNet is a near-real-time satellite-based oil spill and vessel monitoring service operated by EMSA) (EMSA, 2011), and being able to run simulations forward and backwards based on the detected slicks.

The Dynamic Risk Tool has been tested and used several times in real time. However, further work will include sensitivity analysis to different environmental conditions, ship traffic conditions, and drift modeling options. This system is also being updated in the scope of ARCOPOL PLUS where among other things, a post-processing system / hindcasting module will be included (exactly to simulate different past scenarios), as well as a possible incorporation of individual ship information (increasing accuracy in the quantification of probability of spill accident) from EMSA's Ship Risk Profile in THETIS system. This system will also be installed and applied in the Galician Coast.

Finally, all these decision support systems, and MOHID OIDM itself, provide a "best guess" solution / trajectories. In the future, efforts should be done to quantify model uncertainties under stochastic methods, being able to, in the end, supply decision makers with "minimum regret" solutions, as well as probability maps for the modeled scenarios.

III.2.5 Acknowledgments

This research has been supported by EASYCO (contract nr. 2008-1/002), ARCOPOL (contract nr. 2008-1/061) and ARCOPOL PLUS (contract nr. 2011-1/150) - all funded by EU Atlantic Area), and DRIFTER project (funded by AMPERA, FP VI). The authors would like to thank Marine Pollution Response Service from Portuguese Maritime Authority (DGAM) for the exchanged information.

III.3 A new modelling toolkit for managing oil and chemical spills in Western Europe and Morocco's Atlantic coast: the Lisbon Agreement and MARPOCS project

Abstract

The Lisbon Agreement, recently ratified by Spain, Morocco, France, Portugal and EU, envisions the regional cooperation in the case of marine pollution incidents. Transnational strategies to face marine pollution with oil spills and hazardous and noxious substances (HNS) have been under development in different regions. However, the Atlantic sub-region involving Morocco, Madeira and Canary Islands - environmentally sensitive and socio-economically dependent upon marine resources and marine-based tourism - has not been similarly prepared in an integrated fashion, despite the increasing oil & gas prospecting and drilling activities developed in this area.

MARPOCS (Multinational Response and Preparedness to Oil and Chemical Spills) promotes the implementation of a common operational framework supported with novel model-based decision support systems (DSS), adapted to the region and supported by cross border cooperation, implementation and training of local, regional and national authorities. Built on previous EU efforts, strategies and R&D projects, the modelling toolkit to implement in MARPOCS includes:

- Operational and tactical model-based DSS's supported by 3D oil & HNS spill modelling system (MOHID), using new and/or improved high resolution metocean forecasting systems.
- Automatic early warning spill forecasting system (back and forth in time) connected to existing maritime surveillance automatic services (EMSA[1]'s CLEANSEANET service: satellite-based oil spill detection).
- Shoreline holistic risk mapping from spills in the area of interest, in both real-time and historic periods.

[1] European Maritime Safety Agency

The adopted strategy will strengthen capacity for mutual assistance and multinational preparedness and response to accidental pollution episodes in this cross-border sub-region, as planned in the Lisbon Agreement.

III.3.1 Introduction

III.3.1.1 The geographical context

The area of study – the Lisbon Agreement area –, particularly vulnerable to marine pollution incidents, is an Atlantic geostrategic area with rising oil and gas prospecting and drilling activities over the last few years, but where joint and transnational cooperation for improvement of preparedness to oil and HNS pollution has not been sufficiently promoted yet.

III.3.1.2 The Lisbon Agreement

The Lisbon Agreement is an international legal mechanism ratified in 1 February 2014, by Portugal, France, Morocco, Spain and the European Union, to ensure cooperation between the Contracting Parties in the case of giving a pollution incident. With geographical boundaries (see Figure 24) with Bonn Agreement (North Sea) and Barcelona Convention (Mediterranean Sea), the Agreement establishes the obligation of the Contracting Parties to create their own intervention agencies and to set their own national plans of action.

Figure 24 – Lisbon Agreement area

The Lisbon Agreement includes the following goals:

- To contribute to develop and establish a set of directives on the practical, operational and technical aspects on a joint action against pollution of the marine environment by hydrocarbons and other harmful substances in the area covered by the Agreement, or outside, if appropriate.
- To strength the capacity for mutual assistance and to facilitate the cooperation between the Contracting Parties of the Agreement in the combat to the marine pollution by hydrocarbons and other harmful substances, particularly in cases of urgency, when the danger to the marine environment is considered serious.
- To assist the Contracting Parties in order to install and equip pollution combat Centers able to act quickly and effectively in case of giving a pollution incident, according to the established and trained in advance plans.
- To provide assistance to the Contracting Parties, when such help is need, to establish a way of acting quickly and effectively on combating pollution caused by hydrocarbons and other harmful substances.
- To create communication and operation technical means to facilitate information exchange, technical cooperation and training between the Contracting Parties.
- To contribute, if requested by the Contracting Parties, to equip the wharfs for loading and unloading of hydrocarbons, as well as repair ports, located at the coasts on the geographical scope of the Agreement, with its own facilities for the reception and treatment of ballast water and water for cleaning tanks of vessels.

Similarly, and if requested by the Contracting Parties, CILPAN should cooperate to equip the ports with reception facilities to clean own mixtures of hydrocarbons and other wastes from ships. These facilities should have sufficient capacity to meet the needs of the vessels, without causing them delays.

To sensitize the Contracting in ensuring the compliance with the other International Conventions in the area of pollution of the marine environment.

III.3.1.3 Research and technological developments (RTD) to face oil and chemical spills

The need for regional and transnational cooperation in the Lisbon Agreement Area to face marine pollution has been previously demonstrated by historic accidents in Spanish, Moroccan, French and Portuguese coasts. Prestige oil spill was the latest big event in this area involving multiple countries. After this, huge efforts have been developed by the European Commission in order to promote and improve cross border cooperation and regional strategies to face the threats of oil spills. As example, several different RTD projects in the Atlantic Area were objectively designed to develop and improve methodologies, operational tools, manuals, and strategies to a better planning, prevention, preparedness and responding to oil spills: EROCIPS, ARCOPOL, ARCOPOL+, ARCOPOL platform, SPRES (all of them in EU Atlantic Area Programme), ISDAMP (EU's DG-ECHO), DRIFTER (AMPERA Era-net VI Framework Programme). Some of these projects (particularly DRIFTER, ARCOPOL+ and ARCOPOL platform) addressed the preparedness and response to chemical spills as well. More recently, and in the same area, the European project MARINER is exclusively focussed on HNS.

In parallel, a wide group of other European RTD projects and initiatives (e.g. Copernicus Marine Services) were indirectly connected to the increasing operational capacity for oil spill forecasting in this area.

Thus, in this post-Prestige era, and after all these years, the national, regional and local authorities in the NE Atlantic region, may now expect that the operational capacity in terms of state-of-the-art modelling technology is better than ever before. In nowadays, we can observe several exchanges of information and methodologies between the competent authorities, and a much better knowledge about the potential affected zones.

And in relation to HNS spills, recently approved projects (e.g. MARINER) offer positive indications for the future capacities in the area, having in mind the operational limitations to prepare and respond to these specific marine pollution hazard, due to several different aspects (see chapter HNS: An emerging threat).

Nevertheless, not all the areas in the NE Atlantic, and particularly in the Lisbon Agreement Area have been equally subject of study, research, operational investment and cross border cooperation in relation to oil and chemical spills.

One of the examples of regions being less active in terms of RTD efforts from the national and European levels, in order to directly improve preparedness and operational capacity to respond and mitigate spill impacts, is exactly the area covering Madeira archipelago (Portugal), Canary Islands (Spain) and Atlantic Moroccan coast. Although some efforts could / can directly or indirectly improve the operational capacity to the related threats, they have some limitations:

- Mainly national initiatives without direct interaction with neighbourhood regions (e.g. SAMOA);
- European regional projects with more than 10 years old (ALERMAC - Interreg IIIB Açores-Madeira-Canarias);
- International efforts not directly focussed in the preparedness and response to oil or chemical spill issues (CLIMARCOST, CLIMAAT - both Interreg IIIB Açores-Madeira-Canarias).

III.3.1.4 Coastal vulnerability

Madeira Archipelago, Canary Islands and Atlantic Moroccan coast compose a specific region that is in fact environmentally sensitive and socio-economically dependent upon marine environmental resources and marine-based tourism. With millions of tourists visiting these regions every month, tourism represents 20% of GDP in Madeira, 32% in Canary Islands, and more than 10 % in Moroccan country. These numbers tend to grow, as the political instability and security issues continue to threat other neighbourhood regions.

Apart from this, the fisheries sector is also an economic pillar for these countries. Being the largest fish market in Africa, Morocco's fishing sector accounts for 3% of Morocco's GDP. Canary Islands has 9% of the whole Spanish fishing fleet, with Port of Tenerife being the first Spanish fishing port with approximately 7500 tons of fish caught. In fact, Spain has the third biggest fishing fleet in Europe.

III.3.1.5 Spill probability and frequency

A group of factors also contribute to increase the probability of having marine pollution incidents in this area. Intense shipping traffic in the Canary Islands (particularly in Gran Canaria and Tenerife Ports) is just one part of the equation.

The recent and intense oil and gas prospecting and drilling activities in the area are increasing the awareness on potential environmental threats. Morocco has seen a surge in transactional activity over the past years. Major operators such as Chevron and BP have taken large offshore acreage positions in Morocco (Figure 25). Other operators in the country include Kosmos Energy, Tangiers Petroleum, and Petróleos de Portugal-Petrogal SA.

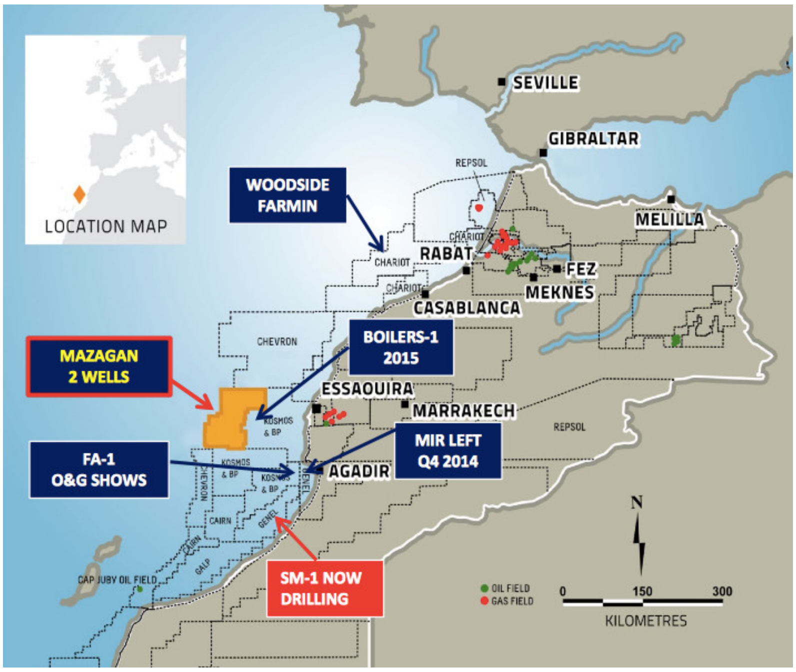


Figure 25 - Prospecting activity in Moroccan coast (source: Pura Vida).

These permits have in turn led to an unprecedented level of drilling activity and introduced the possibility that Morocco's offshore development may soon expand.

Apart from the future risks, past incidents were already recorded in these areas, some of them very recently:

- Aragon's (Madeira): On the 29th December, 1989, whilst under tow following steering gear failure, the Spanish tanker ARAGON (238,959 DWT, built 1975) suffered heavy weather damage some 360 miles off the coast of Morocco. This resulted in the loss of about 25,000 tonnes of Mexican Maya crude from the No.1 centre tank. The oil drifted in a south westerly direction, arriving after three weeks in a highly emulsified state at the east coast of Porto Santo, a small island to the north of Madeira. Porto Santo has the only golden sand beach in the Madeira archipelago with an important associated tourist industry. (ITOPF 2016a). The efficiency of the clean-up teams helped avoiding an ecological disaster. Only a small quantity of oil reached the rocky shores of Madeira and the desert islands. These islands are sparsely populated but are the home of fragile species like the monk seal which is an endangered species, and colonies of sea birds which are generally the first affected by pollution. (CEDRE, 2007). In fact, this accident was an important event to raise the regional awareness for the problematic on oil spills at sea, and the need of mutual and cross-border cooperation in the region of NE Atlantic.

- Silver (Morocco): On 23rd December 2013, after encountering heavy weather, the chemical and product tanker SILVER (4,401 GT; built 2001) grounded on a sandbank off the coast of Tan-Tan in South Morocco while entering the port of El Ouatia. The vessel was carrying 4,940 tonnes of Heavy Fuel Oil (HFO) 380 as cargo, 190 tonnes of HFO 380 as bunker fuel and 24 tonnes of Marine Gas Oil (MGO). The ship was travelling from the Canary Islands when it ran aground with heavy waves dragging it towards a rocky area, sparking fears of an oil slick on Morocco's Atlantic coast. A Lanzarote Cabildo statement said there was a real risk of contamination and it had formally requested information from the Moroccan Consulate on the extent of the problem. A relatively small volume of oil was spilled from both the cargo and bunker tanks. This oil was contained in a small and very exposed area of the shore (ITOPF, 2016b). Once again this incident raised the need for cross-border cooperation protocols communication sharing, and real-time assessment of risks associated to oil spills.
- Oleg Naydenov (Canary Islands): The Russian fishing ship 'Oleg Naydenov' sank about 15 nautical miles south of Gran Canaria in the Canary Islands in April, 12 2015, after a fire that was burning for days spread throughout the vessel. The trawler sank with around 1,409 tons of fuel inside the tanks to a depth of 2,400 meters. The subsequent inspection of the wreck found that several leaks had sprung from the vents, hatches and cracks in the plate sending oil sludge to local beaches, including Veneguera, Tasarte and Taurito. A total of 528 m3 of oily waste was collected (World Maritime News, 2015).

The described past accidents put on evidence the high probability of contamination in the areas of study.

III.3.2 HNS: An emerging threat

One of the main pressures affecting the marine environment today results from chemical pollution: the release and effects of chemicals, particles, industrial, agricultural and residential waste, in marine environments. Worldwide, the production of chemicals is increasing with a total production volume expected to double in comparison with 2000 levels by 2024.

Consequently, the volumes shipped increases every year, with maritime chemical transport having more than tripled in the past 20 years (CEDRE and Transport Canada, 2012), with some of these substances ending up in the marine environment. The threat of a chemical spill at sea concerns many public and private interest groups as the pollution caused is often invisible and may appear difficult to manage.

Like oil spills, chemical marine pollution may also result in harmful effects on aquatic species and wildlife. Although spill accidents with hazardous and noxious substances (HNS) are not so frequent as oil spills, they carry additional challenges and difficulties to responders, environmental managers and modellers, due to a variety of reasons: a) HNS can affect human health; b) the wide panoply of different products transported (Häkkinen and Posti, 2013); c) the differences in physical and chemical properties between substances; d) their different behaviour in the environment.

The increasing awareness for these problems (EMSA, 2007), reinforced by some high impact pollution events in the past, is resulting in the need for development of policies and measures to protect the marine environment from chemical pollution.

In this context, improving models to properly simulate the fate and behaviour of chemical substances on the marine environment can feed decision support systems to help managers, decision-makers and authorities in the assessment of environmental risks associated to these types of marine pollution. These models may also improve preparedness and response to accidental chemical pollution episodes, enabling marine pollution authorities to anticipate the environmental impacts, and therefore providing shorter response times to these types of accidents, which are very hard and complex to manage.

A small number of chemical spill modelling tools are available for investigating processes and environmental impacts, or planning and contingency arrangements, when compared to oil spill modelling software.

III.3.3 MARPOCS project

The context described above is in fact the reason for the development of MARPOCS project. Indeed, although HNS spill accidents are not as frequent as oil spills, their impacts, the multiplicity of products and increasing volume transported justify the development of regional and cross border capacities to respond to both spill types. This is particularly relevant in the studied area, which is environmentally sensitive and socio-economically dependent upon marine resources and marine-based tourism, and where recent incidents raised concerns about the environmental protection associated to spills.

Built on previous EU efforts, and in compliance with parallel international protocols (e.g. OPRC-HNS), strategies and current EU RTD initiatives, MARPOCS is a RTD project that promotes a common operational framework supported with state-of-the-art model-based decision support tools and exercises for oil and HNS spills, adapted to the region and supported by cross border cooperation, implementation and training of local, regional and national authorities. This strategy will strength the capacity for mutual assistance and multinational preparedness and response to accidental pollution episodes in this cross-border sub-region, as planned in the Lisbon Agreement.

The next chapters will describe the methodology followed for the development and implementation of the project in the area of study.

III.3.4 Modelling methodology

The overarching goal of this MARPOCS is to take advantage of previously developed work at international and EU level in different aspects of accidental marine pollution, and to develop and implement an integrated operational framework for preparedness and response to oil and HNS spills in the Atlantic sub-region involving Morocco, Madeira and Canary Islands (see Figure 26) in the context of Lisbon Agreement, making it easily transferable and extendable to other areas.

Figure 26 - MARPOCS implementation zone: The Atlantic sub-region including Morocco, Canary Islands (Spain) and Madeira (Portugal), covering the Southeastern geographical scope of the Lisbon Agreement.

The general objective is achieved by the sharing and development of common guidelines, methodologies, model-based decision support tools and exercises adapted to the regions of study and promoted by effective implementation and training of local, regional and national authorities. MARPOCS also promotes the exchange of modelling technologies and information between all the partners, and between authorities of the different countries. The specific objectives comprise:

- Implementation of a common set of operational and tactical model-based decision support systems (DSS) supported by a previously developed generic 3D oil & HNS spill modelling system (MOHID oil and HNS lagrangian components), updated and calibrated for HNS (studied in HNS-MS and complemented with MARPOCS) using new or improved high resolution metocean forecasting systems.
- Automatic early warning forecasting systems connected to existing maritime surveillance technologies and automatic services, like EMSA's CLEANSEANET service and AIS systems.
- Characterization of shoreline holistic risk from spills in the area of interest, in order to identify "hot spots" and to better manage the distribution of response resources.
- Training sessions, courses, exercises and hands-on demonstrations, with special focus on emergency preparedness or response scenarios involving multiple nations.

The implementation of this operational framework is dependent on application of numerical modelling systems, namely:

- generic on-demand oil, chemical and inert spill simulations, in both deterministic (best guess solution) and probabilistic mode, and easily transferable to other areas outside the project.
- metocean operational forecasts for the project region.

III.3.4.1 MOHID modelling suite

The whole project structure involving oil and chemical spill simulations, including risk mapping tools, will be based on MOHID community modelling suite.

MOHID is a public-domain open-source system, developed following a modular structure combined with object oriented programing (Neves, 2013). The model is freely available for public access, since it is integrated in MOHID numerical modelling system which follows a FOSS (free / open source software) strategy.

MOHID (www.mohid.com) is an environment modelling system dealing with transport and with biogeochemical transformation processes in complex geometries. MOHID was developed to be used by researchers and by professionals and to be applicable to a large range of scales and physical conditions. Researchers require tools able to test hypotheses and compare options, while professionals require efficiency for quick results production. A wide range of scales (in both aquatic and land environments) requires the consideration of the corresponding transport processes and of interactions between scales. MOHID modular structure allows this system to be used to simulate (separately or in an integrated fashion) hydrodynamics, water quality, sediments transport, benthic processes, plume dilution and dispersion, among several other processes.

Oil and HNS modelling components are integrated on MOHID lagrangian transport module, where simulated pollutants are represented by a cloud of discrete particles (or super-particles) advected by wind, currents and waves, and spread due to random turbulent diffusion or mechanical spreading.

MOHID lagrangian module (Ascione Kenov, et al., 2014) can be run simultaneously with the hydrodynamic model (currents, water temperature, salinity, etc.), or in "offline" mode. In both modes, this model is able to digest currents, water properties, wave parameters and atmosphere properties from different model providers. Additionally, MOHID lagrangian module allows backtracking / modelling, as well as a multi-solution approach (Fernandes, et al., 2013) (generating computational grid on-the-fly, and using the available information from the multiple metocean forecasting solutions available).

The user interaction with MOHID lagrangian module is presently available through different desktop and web-based platforms (Fernandes, et al., 2013), allowing users to define scenarios for model simulations, integrating updated metocean forecasts and generating results in seconds.

The diversity and capacity in the integration of MOHID lagrangian module with powerful and yet simple simulation tools (Fernandes, et al., 2013) is essential to the seamless integration and implementation of MARPOCS strategy and model-based DSS.

III.3.4.2 MOHID oil spill module

The oil spill module is integrated in lagrangian component of MOHID, and has been widely used and validated in oil spill applications, exercises and real situations (Carracedo et al., 2006) across the world, allowing the simulation of all major oil transport and weathering processes at sea. The source code of oil spill modelling system includes full 3D movement of oil particles, wave-induced currents, and oil-shoreline interaction (Fernandes et al., 2013), as well as a first approach for blowout emissions (Leitão, 2013).

MOHID 3D oil spill model is being adapted to simulate deep water blowout spill scenarios with state-of-the-art technology, taking advantage of scientific and technological developments associated to underwater oil spill measurements and the increasing understanding of water column behavior of oil. In more detail, this research work compiles and adapts the modelling software to enhance oil/gas dispersion/droplet evolution including breakup and coalescence. A correct quantification of jet / near field plume dynamics of underwater oil released in the subsea is to be included and integrated with subsequent far field modelling processes. The conditions and kinetics for gas hydrate formation and decomposition are also addressed. Most of these developments are in progress, taking advantage of synergies with MEOPAR project (Dalhousie University, 2016).

The oil spill model is also being adapted to include environmental effects modelling component, allowing to evaluate the biological impacts in fauna and flora (fishes, benthic organisms, birds and marine mammals), based on the estimation of exposure probabilities and time associated. This modelling component depends on the toxicological information available for the different species being studied.

Last, the transport models are being updated to provide probabilistic maps from ensemble forecasts with perturbed parameter schemes (based on uncertainty estimations for the most relevant parameters that influence the spill – e.g. metocean forcing conditions, spill release time and location).

Oil spill model validation will be mainly based on the field measurements with drifters during the project, comparing drifter measured trajectories with model simulations.

III.3.4.3 MOHID chemical spill module

In the scope of MARPOCS, MOHID chemical spill modelling software is being subject to a calibration process based on laboratory measurements from different HNS, as well as programming improvements mainly related with performance, results visualization and interactions with the benthic layer.

MOHID chemical spill module is in fact a recent implementation inside MOHID. In this model, the spilled mass is tracked through phase changes and transport, with all reaction products assumed to move together – chemical reactions are not specifically addressed in the model. The loss of chemical by reaction to some other form no longer of concern is included in degradation, which is estimated assuming a constant rate of "decay" specific to the environment where the mass exists (i.e., atmosphere, water columns, or sediment). The model estimates the distribution of chemical (as mass and concentrations) on the water surface, on shorelines, in the water column, in the sediments and at the bottom. Model tracks separately surface floating chemical, entrained droplets or suspended particles of pure chemical, chemical adsorbed to suspended particulates, and dissolved chemical. The phase changes are computed independently for each particle every time-step, and the probabilities of one particle change from one phase to another (e.g. entrained to dissolved) is (pseudo-)randomly obtained, based on the algorithms that quantify the mass balances in the different processes. Therefore, a correct modelling using this kind of approach obviously require a great amount of particles in the simulation, in order to properly reproduce phase changes when slow processes / small mass transfers are involved.

Chemical mass is transported in 3D space and time. The horizontal movement is controlled by currents, wave-induced velocity (Stokes Drift), wind-drift velocity in the surface layer (for floating substances), spreading, and horizontal turbulence. The vertical movement is estimated in accordance with vertical advection from currents, rising velocity, sinking velocity, and turbulent dispersion.

These processes were already implemented in MOHID's lagrangian module, and they are also used in the simulation of oil spills. MOHID can simultaneously simulate currents (in the hydrodynamic module), or use an imposed solution (which is called the "offline" solution) from a previous run, or from a different model (or set of models), as long as the outputs accommodate the time period to simulate.

Since MOHID computes the chemical spills using independent lagrangian particles, surface spreading is modelled at three different levels: a) the initial area of the surface slick (based on Al-Rabeh, et al., 2000), which is randomly populated by MOHID with lagrangian particles; b) the increasing surface area of individual particle (adapted from Mackay, et al., 1980a); c) the random movement of individual particles position to reproduce the increasing area of the surface slick (random velocities using diffusion coefficients from Al-Rabeh, et al., 2000).

The vertical velocity of chemical tracers inside the water column (entrained droplets due to breaking waves) is a balance between their intrinsic buoyancy, advection and turbulence. The rising velocity can be estimated by two alternative approaches: a) assuming a double regime (spherical-cap bubble and small spherical droplets) as used by Liungman and Mattsson (2011); b) three-regime formulation, as proposed by Zheng and Yapa (2000).

In respect to weathering processes, MOHID includes the vertical entrainment from breaking waves, evaporation from surface, and volatilization from water column, dissolution, partitioning / sedimentation (adsorption to sediments), resuspension and degradation.

The entrainment of the chemical in the water column can be estimated by the approach of Delvigne & Sweeney (1988) and Delvigne and Hulsen (1994). Entrained droplet diameters can be optionally estimated based on a) user-defined definition (unique value); b) half of the mass median droplet diameter (Spaulding, et al., 1992) or c) pseudo-randomly chosen diameter based on a diameter class distribution computed using Delvigne and Sweeney (1988) formulation. Particle depth is randomly chosen between Surface and maximum intrusion depth (Tkalich and Chan, 2002).

The evaporation rate from surface floating slicks from chemicals is computed with Kawamura and Mackay, 1987, and assuming that the transfer of mass from liquid to the air is limited by molecular diffusion across a stagnant boundary layer in the air above the chemical's surface (Mackay and Matsugu, 1973). A correction for evaporation rate is included for volatile chemicals, according to Brighton 1985.

Volatilization of dissolved components from the water column to the atmosphere occurs as they are mixed and diffuse to the sea surface boundary and enter the gas phase. This process is computed from the chemical's vapour pressure and solubility, as outlined by

Lyman et al., (1982), based on Henry's Law and mass flux being controlled by diffusion in both the water and the air near the interface (Hines and Maddox, 1985).

Dissolution is estimated for spillets in the surface and in droplets dispersed in the water column. Surface slick dissolution is based on the hypothesis of a flat plate (the slick), and the droplets in water column are assumed to be spherical, with the dissolution treated as a mass flux across the surface areas, according to Mackay & Leinonen, 1977. The dissolution from entrained small droplets is much faster than from surface slicks in the shape of flat plates (which is insignificant), because the surface area to volume ratio is higher for smaller spherical droplets.

Contaminants in the water column are carried to the sea floor primarily by adsorption to suspended particles and subsequent settling. Dissolved chemical in the water column is assumed to adsorb to natural particulate matter based on linear equilibrium partitioning theory, with constant proportions between dissolved and adsorbed concentrations, and dependent on suspended particulate concentration. Substance adsorbs to "silt" particles, and the adsorbed fraction is transported by Stokes Law, and subject to other vertical forces in the water column (e.g. turbulence).

Chemically contaminated particles deposited at the bottom can be re-suspended if bottom current velocity is above a specified threshold (default = 0.2 m/s).

Degradation of a chemical can occur at different environments (atmosphere, water column and sediment) by different processes (biological, chemical or photochemical). Since this degradation processes are not specifically addressed in this model (spilled mass is modelled in terms of transport and phase changes), a constant decay rate specific to the environment where the mass exists is assumed, in order to determine the degradation / loss of chemical to some other form no longer of concern.

The outputs of the chemical spill software developed include the evolution of particles position and state over time, as well as different parameters in 3D or integrated over the vertical column (e.g. mass, concentrations and maximum concentrations).

As for oil spill model, chemical spill model validation will be mainly based on the field measurements with drifters during the project, comparing drifter measured trajectories with model simulations.

III.3.4.4 Metocean forecasting systems

The implementation, calibration and validation of metocean (currents, waves and meteorological) models covering the areas of study will be performed, in order to provide operational outputs with sufficient spatial resolution to feed transport models and risk mapping tool, as well as to adequately simulate safety and marine pollution incidents. A new set of models will be implemented in Moroccan Atlantic coast and Canary Islands (MOHID for hydrodynamic modelling; WRF for atmospheric modelling; WW3 for wave modelling), and in Madeira the already available operational metocean modelling infrastructure (Oceanic Observatory of Madeira, 2016) will be improved to a courser resolution.

Model forecasts will be daily generated, covering the MARPOCS areas of study, and published online in common formats and platforms commonly adapted by the modelling community (netCDF files in THREDDS / OPENDAP catalogue servers), facilitating integration in the developed common repository (chapter III.3.5.5) and therefore in the decision support tools.

This metocean modelling infrastructure will be also available to potentially provide support to multiple purposes outside of the project direct scope, including recreational coastal activities, scientific research initiatives or even water quality management.

Model validation will be initially pursued with available external data sources (or historic data from the partners), and then with the data obtained from field measurements inside MARPOCS and with cooperation with other ongoing partner monitoring programmes. The metocean model validation will make use of ARGO float network, remote sensing imagery, fixed stations, and any other in-situ data sources previously obtained and available for the areas of study. The combination of all these data will provide a proper model validation, and ultimately the definition of model skill parameters, useful for estimation of uncertainty (needed for probabilistic transport modelling purposes).

III.3.5 Decision Support Systems & data services: preliminary results

The implementation of MARPOCS framework is based on the improvement and adaptation of model-based tools that can directly contribute to a more robust decision making from maritime authorities, contingency planners and emergency operators in the MARPOCS zone. These developments supply the decision makers with: a) an on-demand oil, HNS and inert 3D spill simulator providing deterministic and probabilistic forecasts in MARPOCS area; b) an automatic oil spill early warning system providing automatic forecasts based on satellite-detected spills from EMSA's CLEANSEANET service; c) a shoreline holistic risk mapping tool for dynamic monitoring of shoreline risk from spills based on real-time ship traffic.

The different model-based decision support tools mentioned above are integrated in a responsive web-based platform working as a Common Operating Picture (COP) available in the region of study, allowing to visualize all metocean model forecasts as well, and improving maritime situational awareness. This COP is directly fed by an integrated and polycentric meteo-oceanic data framework, including a common model output sharing platform, as described in III.3.5.5.

The whole pack of MARPOCS decision support systems and data services integrates Action Seaport (Action Modulers, 2016) (see Figure 27), which is an integrated information system for safety and environmental performance and risks focused on Ports, but is applicable to local, regional and national authorities, and is potentially applicable in any region, depending on the data availability (e.g. metocean forecasts, satellite images, etc.).

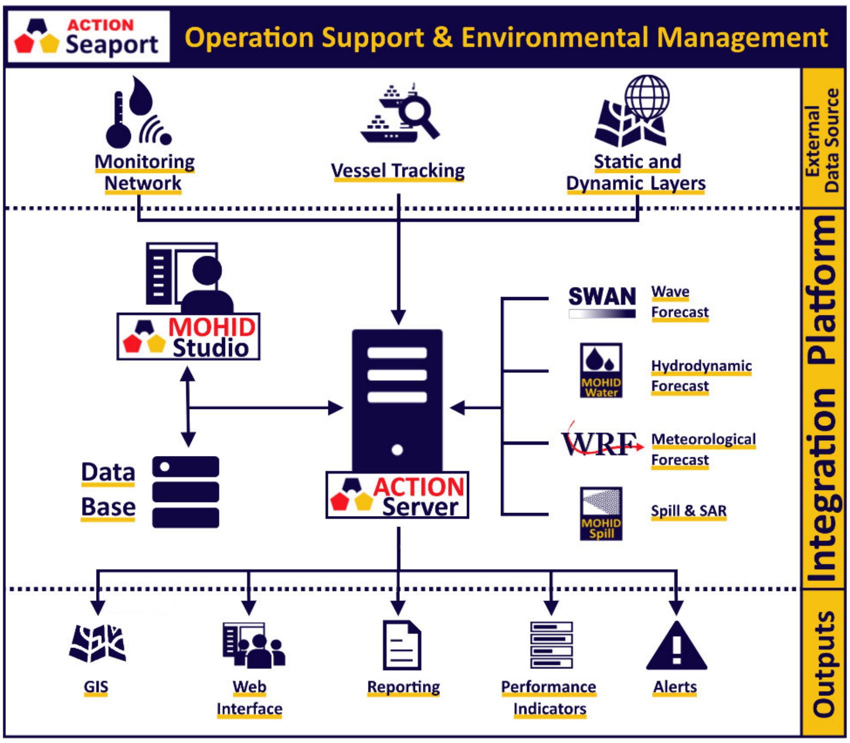


Figure 27 - Action Seaport: information flow diagram.

III.3.5.1 On-demand oil and chemical spill simulation

The implemented system establishes a seamless connection with meteo-oceanic central server to download the forecast data needed, and then use it to force transport modelling system. This component is able to estimate the fate and behavior of the properties and processes of the different types of pollutants, using MOHID and following a deterministic approach (best guess solution) as well as probabilistic maps (with uncertainty estimations) in forecast mode (to manage real time emergency situations), but being also able to process simulations from past scenarios (usually needed in risk assessment and planning situations). The probabilistic outputs of the tool include probabilities of concentrations (exceeding a prescribed minimum threshold value, maximum and mean values), and minimum travel times (corresponding to the shortest time required to reach any point or concentration exceeding the defined threshold), providing associated errors. The system includes the possibility of oil spill simulations from surface and underwater / deep water blowout spill scenarios.

The end-user is able to configure a chemical spill by selecting a chemical product from HNS databases embedded in the system and dynamically connected to external providers. Three different providers can be used: RBINS (in the scope of HNS-MS – co-funded by EU DG-ECHO); CEDRE or EMSA (MAR-CIS); CIIMAR (in the scope of MARINER project – co-funded by EU DG-ECHO).

On-demand oil spill simulations can be based on oil slick polygons provided from EMSA's CLEANSEANET oil spill satellite detection service, to run forward and backwards in time (to provide support in the tracking and identification of pollution sources), and also allowing to study the effect and efficiency of applied booms in simulated scenarios. All these capabilities together increase the tactical and operational capacity of this decision support tool.

This on-demand spill simulation tool is available for integration not only in the MARPOCS COP (responsive web platform – e.g. see Figure 28) but also as a plugin in MOHID Studio GIS system (Figure 29), or EMSA's CLEANSEANET user interface.

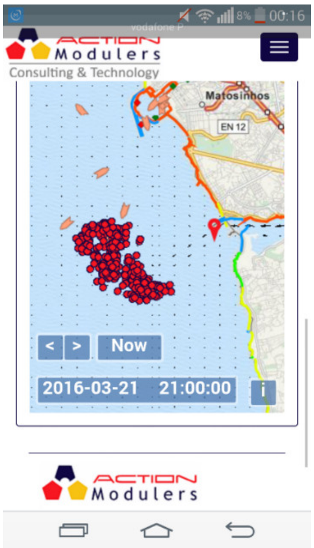


Figure 28 - On-demand oil spill simulation (red dots) + vessel positions + shoreline economic sensitivity index, in smartphone.

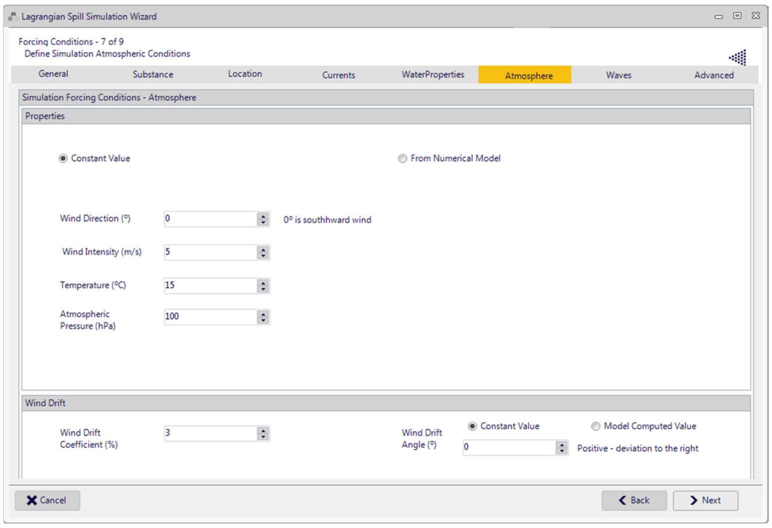


Figure 29 - On-demand spill simulation in desktop / laptop environment (integrated in MOHID Studio).

III.3.5.2 Preliminary results from the new chemical spill model

Although MOHID oil spill model has been widely used in different real, operational or schematic scenarios, the chemical spill model is a new implementation in MOHID, and therefore, a battery of different modelling scenarios was chosen to initially evaluate the chemical spill model response to different substances and responding as expected to variable conditions: 9 different substances - one per physical-chemical behaviour class (gas category was not simulated); different wind velocities (3 m/s and 8 m/s); different release depths (0m and 50m); different suspended sediments concentration: 10 mg/L and 0 mg/L. In this paper we analyse a selection of results to illustrate the model response to some of these parameters.

The spatial geometry used for the simulations is based on a tank with a constant depth of 96.5m. A constant horizontal spatial step of 100m (dx = dy) was used for the whole domain, as well as 51 vertical layers with a variable depth (starting with approximately 10 cm at surface layer and with 3.86m at the bottom). Current velocity is not included, and only surface advection due to wind (wind drag effect) is included in the simulations. Turbulent dispersion and wave-driven velocities (Stokes Drift) were also disconnected; therefore, wind is the only horizontal force that controls the particles trajectories. A constant water salinity of 36 ppt was used, as well as a constant temperature of 16ºC. Degradation process was kept turned off by default.

The schematic and simplistic approach followed for the modelling scenarios was adopted to clearly reduce the number of variables controlling the results, and isolating the influence from the chemical specific parameters and processes programmed.

Changes in wind speed can affect different processes. Thus, a greater wind speed will increase the mass transfer in the evaporation process over the surface slick (Figure 30), but will also increase indirectly the wave height (which in these simulations is computed directly from wind speed) and consequently the diffusive mix depth (obtained from the wave height). These changes will increase entrainment in the water column (due to higher energy from breaking wave), and consequently the dissolution rate (Figure 31).

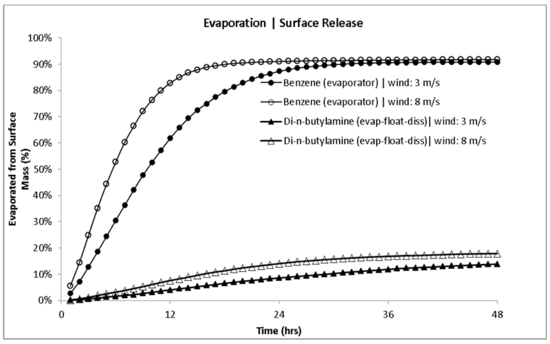


Figure 30 - Mass Evaporated from surface for benzene and di-n-butylamine released at surface waters using different wind speeds (no degradation; suspended sediments concentration = 0 mg/L).

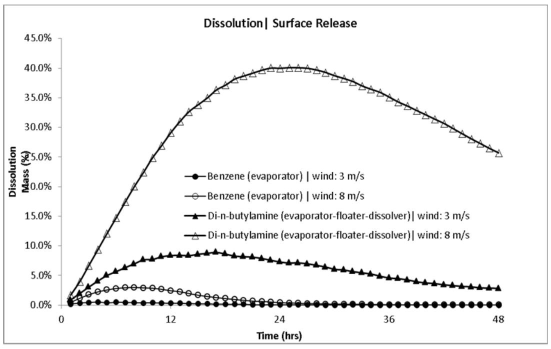


Figure 31 - Mass dissolved from a surface spill of benzene and di-n-butylamine under variable wind conditions (no degradation; suspended sediments concentration = 0 mg/L).

The influence from the release depth was also analysed and compared (Figure 32 and Figure 33). If released at subsurface layers (5m depth), the typical behaviour of floating substances (with density lower than water) with any kind of solubility is the increase in dissolution rates, as buoyant liquid rises through the water column. Model results reproduce the mentioned increasing dissolution for subsurface releases.

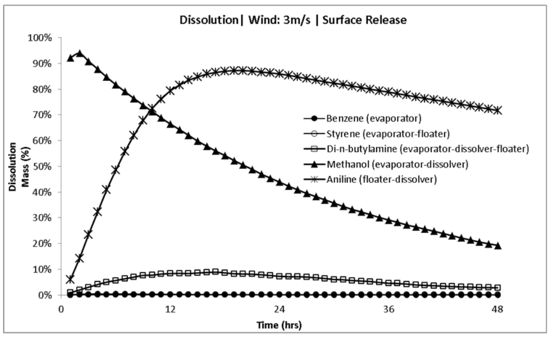


Figure 32 - Mass balance from a surface spill of di-n-butylamine (wind speed = 3 m/s; no degradation; suspended sediments concentration = 0 mg/L).

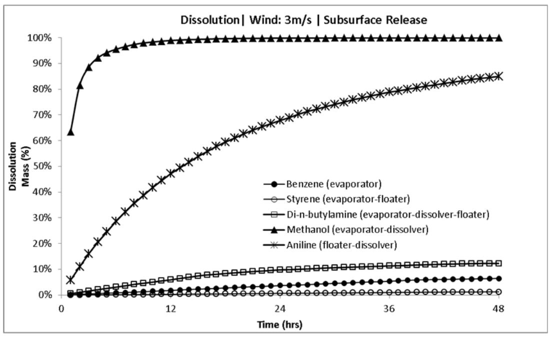


Figure 33 - Mass lost from a surface spill of di-n-butylamine (wind speed = 3 m/s; no degradation; suspended sediments concentration = 10 mg/L).

Hence, the results obtained with the chemical spill model reproduce the expected variations based on the different modelling scenarios deployed. Further tests must now be performed to verify the sediment interactions in seabed (bottom deposition and re-suspension), as well as to apply the whole model in real test cases including 3D hydrodynamic fields and turbulence.

III.3.5.3 Automatic early warning spill forecasting system

An automatic oil spill detection + forecasting system allows the automatic generation and distribution of MOHID oil spill forecasts based on detected oil slicks from EMSA's CLEANSEANET automatic detection service. No human intervention is needed in any part of the system, with results distributed in less than 10 minutes after oil spill detection (usually detection service takes no more than 30 minutes). The main objective of this tool is to provide an immediate first guess to the maritime authorities, with simulations forward and backward in time, facilitating the identification of potential pollution sources.

This work is integrated in the scope of the scientific cooperation protocol between EMSA and MARETEC-IST in relation to oil spill modelling (to establish an automatic link between MOHID and CLEANSEANET), with the technical support of Action Modulers.

The oil spill early warning system is able to provide automatic notifications (by email, and in the near future, by SMS) to selected and authorized end-users with a hyperlink to oil spill forecasts based on the detected spill. Results are able for distribution in multiple platforms and formats, including Google Earth animations (see Figure 34 and Figure 35), MOHID Studio GIS System, and EMSA's CLEANSEANET interface.

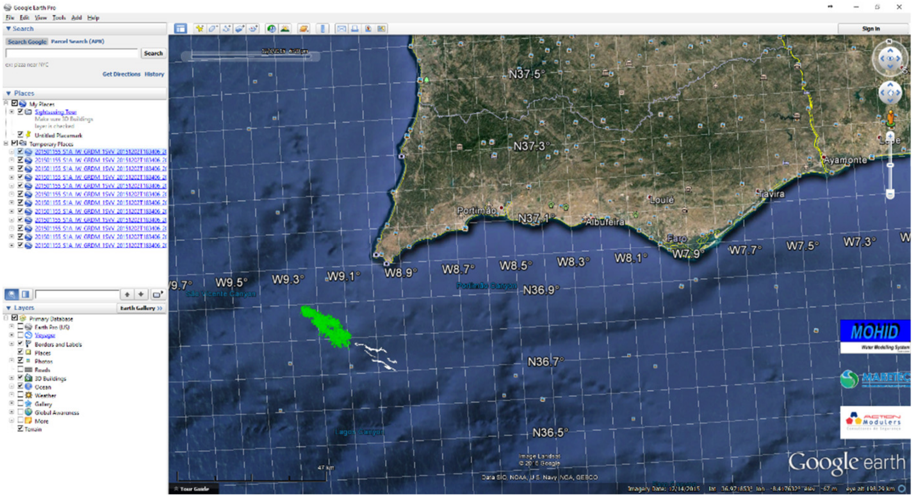


Figure 34 - Visualization of Google Earth output from MOHID-CLEANSEANET oil spill early warning service. Detected oil slick –white polygons; green dots – oil spill forecast (in forward mode) 24 hours after detection.

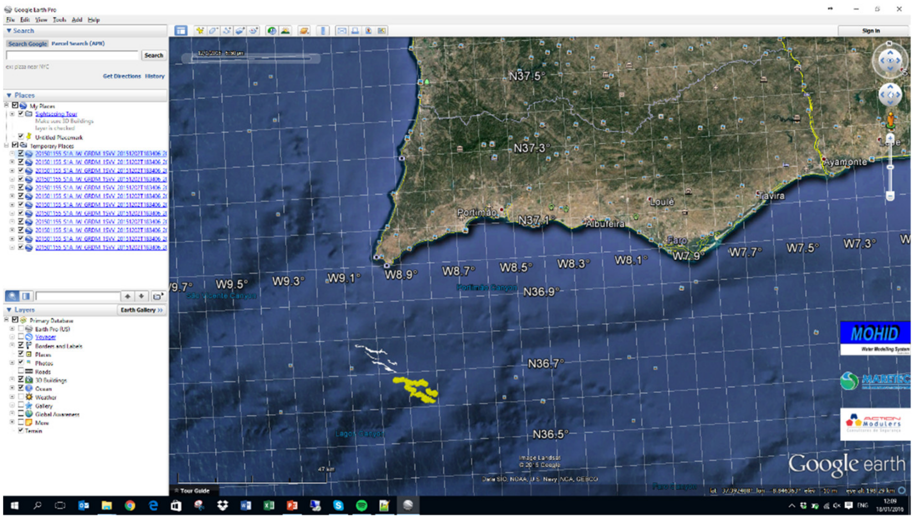


Figure 35 - Visualization of Google Earth output from MOHID-CLEANSEANET oil spill early warning service. Detected oil slick –white polygons; green dots – oil spill forecast (in backtracking mode) 24 hours before detection.

This service will be also available to be integrated in other external web services (e.g. EMSA services, CEDRE emergency department or other satellite-based oil spill detection services that can emerge in the future from the new Sentinel Copernicus service), as well as to be applied in other geographical regions, provided that data formats from detected oil slicks and metocean forecasts are kept in a standardized way, as done in the present implementation.

III.3.5.4 Shoreline holistic risk mapping

A holistic approach to estimate time and space variable shoreline risks from ships is being implemented in the area of study, integrating meteo-oceanic and oil spill forecasts with vessel traffic information (AIS). The risk rating combines the likelihood of an oil spill occurring from a vessel navigating in the study area with the assessed consequences to the shoreline. The spill likelihood depends on dynamic marine weather forecasted conditions and historical accident data. The consequences reflect the hypothetical spilled oil amount reaching shoreline and its environmental and socio-economical vulnerabilities. The oil reaching shoreline is quantified with an oil spill fate and behavior model running multiple hypothetical spills from vessels along time.

The environmental and socio-economical vulnerabilities is quantified following NOAA methodology for Environmental Sensitivity Index, and the socio-economic index is determined from multiple local statistical parameters associated to coastal tourism, fisheries and aquaculture, recreational activities and coastal population.

This decision support system is capable of real-time risk monitoring, integrated in MOHID Studio GIS (Figure 36 and Figure 37) and in the same MARPOCS COP used for visualization of metocean data and on-demand spill simulations. The user interface permits visualization of vessel accident risk, shoreline contamination risk and vulnerability indices, vessel traffic and details, isolated risks caused by specific vessels or isolated risks on specific zones.

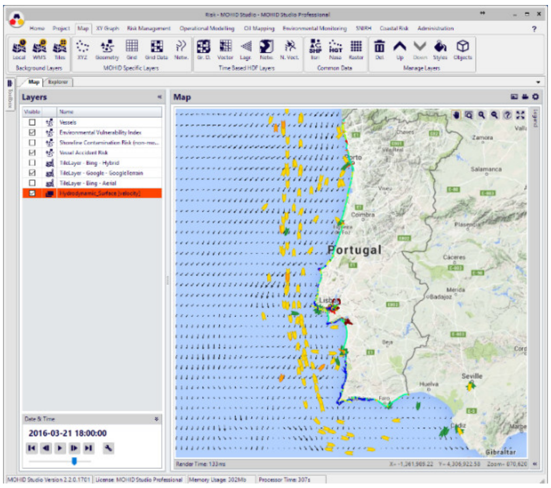


Figure 36 - Instant shoreline contamination risk + vessel accident risk in MOHID Studio GIS

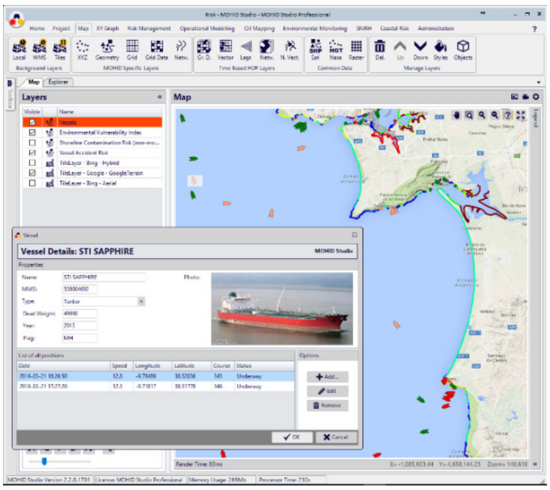


Figure 37 - Detailed information about a selected vessel, in MOHID Studio GIS

This system capitalizes ARCOPOL platform risk assessment tool (Fernandes et al., 2016a), adapting it to MARPOCS area, and consolidating new functionalities, including the risk component from offshore platforms and a new alert system that will send automatic emails or SMS whenever the shoreline contamination risk in the area is expected to rise above a specified risk tolerance threshold level. The integration of metocean + oil spill models with coastal vulnerability and AIS data in the quantification of risk, enhances the decision support model, providing a more realistic approach in the assessment of shoreline impacts, raising immediate awareness for higher risk areas, and to prioritize the tug positioning in function of risks.

The same system can also be used to provide scenario-based risk studies. Therefore, an additional risk assessment evaluation will characterize the impact and risk of shoreline contamination in the area of interest taking in consideration a representative set of historical information, identifying the main "hot spots" and thus providing valuable information to strategically plan the best places for locating emergency response equipment and resources, as well as to define mitigation strategies.

Finally, applying this risk assessment tool also provides a different perspective and understanding on risk in specific zones with calm and / or favorable meteo-oceanic conditions with constant high cargo or tanker traffic in the near-shore area. The developed tool shows that those conditions don't necessarily mean high risks for the shoreline – the existence of wind and currents generating oil transport offshore will significantly reduce the shoreline contamination risk (Fernandes et al., 2016a).

III.3.5.5 Information repository for data sharing

A polycentric information repository will be used as back-end central server. The MARPOCS web platform for visualization of metocean data and simulation of oil and chemical spills, will connect with this back-end central server (Action Server), responsible for model data storage and processing. This server can also be installed locally, in order to feed MOHID Studio local installations.

Therefore, Action Server is the "heart" of the whole operational platform, dealing with model downloading, on-demand and automatic spill simulations and distribution of data layers in multiple platforms, including not only MARPOCS interfaces, but also third-party systems that obtain data using common standards, like OGC WMS (e.g. Google Earth – see Figure 38) or REST API (e.g. browsers, smartphones).

Open Geospatial Consortium (OGC) standards are made through a consensus process and are freely available for anyone to use to improve sharing of the world's geospatial data. OGC standards are used in a wide variety of domains including Environment, Defense, Health, Agriculture, Meteorology, Sustainable Development and many more. REST API allows clients and servers to interact in complex ways without the client knowing anything beforehand about the server and the hosted resources. Through the application of REST architectural constraints certain architectural properties are induced: Performance, Scalability, Simplicity, Modifiability, Visibility, Portability, and Reliability.

Most of these advantages are therefore in line with the objectives of MARPOCS, which intends to build a common platform with the potential for later transferability to other regions, inclusion of more data sources, etc.

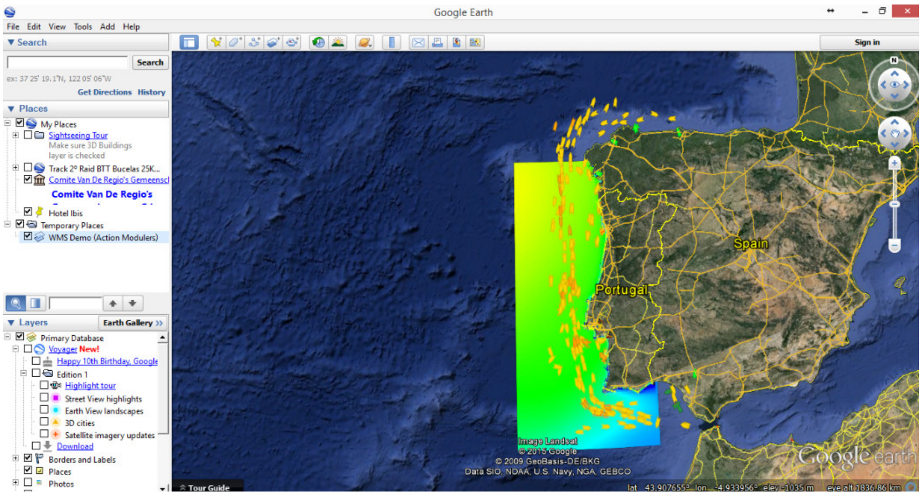


Figure 38 - Visualization of risk layers in a third-party platform (Google Earth), making use of OGC WMS communication protocol

III.3.6 Final remarks

The developments in MARPOCS capitalize as much as possible decision support tools initially developed in other Atlantic area projects, enhancing and improving them in different technical operational aspects, as well as adapting them to the specific needs of the MARPOCS zone and their end users.

The region of project implementation, particularly vulnerable to marine pollution incidents, is an Atlantic geostrategic area, but where joint and transnational cooperation for improvement of preparedness to oil and HNS pollution has not been sufficiently promoted yet. MARPOCS will fill this gap, in line with the Lisbon Agreement, where the main goal is exactly the establishment of set directives on the practical, operational and technical aspects on a joint action against oil and HNS pollution in NE Atlantic.

With partners from all the Contracting Parties, MARPOCS aims to contribute to interagency and mutual cooperation, interacting with European services and networks, EU projects, neighborhood regions or International conventions.

This project also develops a novel and ready-to-use integrated model-based decision support platform, composed with different and complementary modelling components, such as operational probabilistic forecasts with uncertainty estimations, holistic approaches for real time spill risk monitoring, early warning forecasting systems seamlessly connected to automatic surveillance services, a lab-calibrated chemical spill model and an oil spill modelling tool for estimating biological effects.

Specifically, in relation to the developed chemical spill model, the results obtained correctly reproduce the expected variations based on the different modelling scenarios deployed. Further tests must now be performed to verify the sediment interactions in seabed (bottom deposition and re-suspension), as well as to apply the whole model in real test cases including 3D hydrodynamic fields and turbulence. The modelling approach adopted requires a large number of lagrangian particles, however lagrangian model performance was recently improved, and future parallelization will be studied in this context. The developed model is now available to be used by modellers in the scope of environmental studies and planning stages. The ongoing integration of chemical spill model with available decision support tools previously implemented for oil and inert spills will provide an effective and more complete answer to emergency responders, and more reliable than simply generalizing different behavior classes to reproduce the whole panoply of chemicals transported at sea – which is sometimes used in some operational systems, due to the lack of better operational modelling solutions.

The holistic approach for risk assessment enhances not only strategic decisions, but also tactical and operational capacities with real-time risk estimation techniques, opening interesting opportunities for the future both in terms of risk planning and monitoring activities.

A tool like this can improve the decision support model, allowing the prioritisation of individual ships or geographical areas, and facilitating strategic and dynamic tug positioning. The possibility of being used for past or hypothetical scenarios may provide an interesting tool not only for identifying "hot-spots" in terms of shoreline contamination risk, but also to estimate future situations like the increasing of ship traffic or the size and cargo transported by the ships. Using an oil transport model (together with metocean modelling systems) in the estimation of the risk of oil reaching the coastline can provide a more robust and dynamic risk assessment.

Furthermore, the same risk model approach can be considered in the future to estimate other types of environmental threats, including impacts from spills in offshore platforms, impacts from onshore activities and industries involving discharges to the water environment, or even the environmental impact of maritime transport emissions on coastal air quality.

Regarding the implementation of the early warning system for oil spill detection and forecasting, the existing cooperation protocol between EMSA and IST in oil spill modelling activities will allow the development of decision support systems directly connected to EMSA services. An automatic forecasting system linked to the automatic detection service reduces the time between oil spill detection and the provision of oil spill forecasts to end users, increasing the time available for the decision-makers to prepare and take a more robust decision. Automatic generation of backtracking results can also reduce the assessment time to track potential polluters.

The different model-based decision support tools mentioned above will be integrated in a Common Operating Picture (COP) available in the region of study, and efforts will be done to adopt internationally common standards (in particular, OGC compliant open standards), protocols and recommended practices (e.g. upcoming results from OGC's OGP / IPIECA Oil Spill Response COP) to facilitate interoperability challenges between different data providers and GIS systems. Indeed, the complete implemented system will be potentially applicable in any region, depending on the data availability (e.g. metocean forecasts, operational satellite-based oil spill detection services).

III.3.7 Acknowledgments

This work is sponsored by project MARPOCS (co-funded by European Union; ECHO/SUB/2015/713854/PREP08) and MARINER (co-funded by European Union; ECHO/SUB/2015/713785/PREP10).

The authors thank to Portuguese Maritime Authority (DGAM-SCPM) for the cooperation and support in beta testing, as well as to European Maritime Safety Agency (EMSA) for the cooperation and exchange of technical data in the scope of the scientific cooperation protocol with MARETEC (IST). Last but not least, a special thanks to

Marine Traffic for the involvement and provision of AIS data support in the scope of research and development activities within the project scope.

IV Spill modelling and remote sensing: operational tools and hazard mapping

IV.1 Automated system for near-real time prediction of oil spills from EU satellite-based detection service

Abstract

The state-of-the-art in both operational oceanography, remote sensing, and computational capacity, enables now the possibility of developing near-real time, holistic automated services capable of dramatically improving maritime situational awareness to responding to oil spill emergencies.

Based on the European satellite-based oil spill and vessel detection service – CleanSeaNet (EMSA – European Maritime Safety Agency), which distributes oil pollution detection standardized notification packages in less than 30 minutes, a new automated early warning system (EWS) for near-real time modelling and prediction of the detected oil spills was developed. This EWS provides 48-hour oil spill forecasts + 24-hour backward simulations, delivering results 5-10 minutes after the reception of the oil spill detection notifications. These forecasts are then distributed in multiple formats and platforms (e.g. Google Earth, e-mail).

The oil spill fate and behaviour model used in this EWS is part of MOHID modelling system, and is coupled offline with metocean forecast solutions, taking advantage of autonomous models previously run in multiple institutions. The system is currently able to integrate various metocean forecasting systems, being agnostic about the data sources and applied locations, as long as their outputs comply with commonly adopted formats, including CF compliant files or CMEMS (Copernicus Marine Environment Monitoring Service).

The EWS is currently operational in western Iberia, supporting Portuguese Maritime Authority, and is being expanded to neighbourhood regions (from Spain and Morocco) with high resolution metocean models (MARPOCS project funded by European Union Humanitarian Aid & Civil Protection). Taking advantage of the coupling of MOHID oil spill model and CleanSeaNet, an oil spill hazard assessment is made in the Portuguese continental coast, based on the cumulative analysis of drift model simulations from previously detected spills using metocean model data, for a period between 2011-2016.

Although this EWS doesn't replace on-demand operational oil spill forecasting systems, it supports maritime authorities with a fast first-guess forecast solution, allowing:

Anticipation of tactical response (including visual inspection of the spill) and mitigation of the pollution episode;

A more effective identification of the pollution source, and in case of suspected illegal spill, earlier actions towards effective prosecution of the polluter;

In the other hand, the hazard assessment generated is a valuable instrument for the development of efficient planning and prevention strategies.

The EWS can be connected to any satellite-based detection service (inside or outside Europe) as long as the detected oil slicks are automatically distributed in a structured and standardized data format similar to CleanSeaNet.

IV.1.1 Introduction

Oil spills remain a serious environmental risk, as the livelihood and the marine ecosystems can be considerably affected in the event of a significant incident (ITOPF, 2011). The incidence of maritime pollution with oil spills is frequently linked to ship's incidents. Large spills from tankers and oil industry operations have become less frequent in the last few decades. Similarly, the huge number of illegal, small spills are being progressively controlled and reduced. International conventions have provided important preventative measures. In fact, the vast majority of spill incidents are associated to small amounts of released oil (ITOPF, 2015). But the severity of a spill is not only connected to the amount released - for instance, the remoteness of the site or the difficulty of an emergency environmental response are factors that can significantly increase the impact.

In the last years, new ocean and coastal forecasting capabilities have been achieved and resulted in stabilized operational services (e.g. CMEMS - Copernicus Marine Environment Monitoring Service), being now daily accessed and used by several intermediate and final users and downstream services - remote sensing is part of the mentioned operational services. Remote sensing technologies can play an important role in the early detection of these kind of incidents, since Earth observation services are now able to provide realtime and near-real time data, shortly processed, easily accessed, and oriented to multiple integrated maritime services. EMSA's (European Maritime Safety Agency) CleanSeaNet is a good example of a near-realtime remote detection monitoring service. Launched and maintained since 2007, this is an important pan-European operational system able to provide detected oil spill notifications (based on SAR - synthetic aperture radar images) to the EU coastal states in less than 30 minutes (Figure 39).

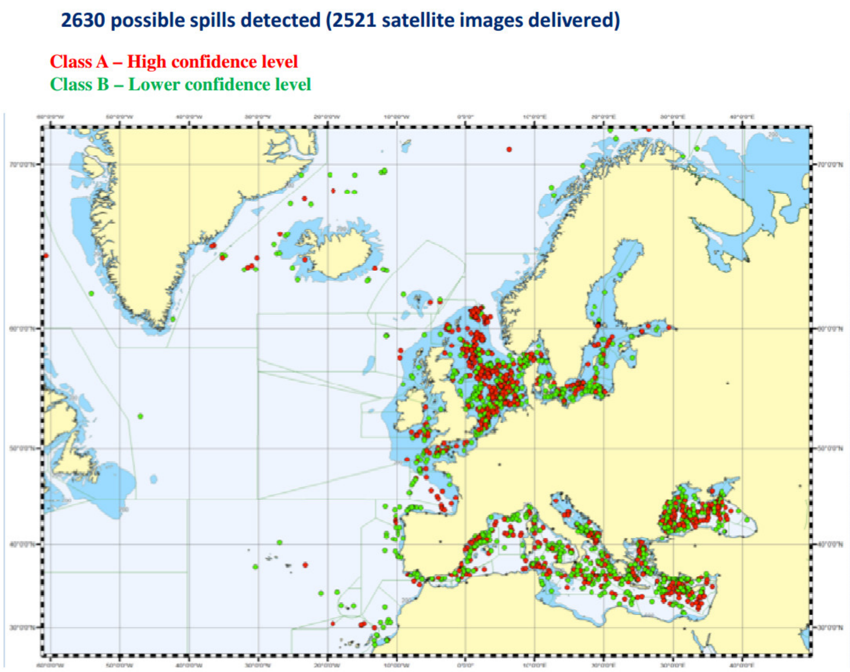


Figure 39 - CleanSeaNet detections in 2014 (Source: EMSA)

Following a regional approach, cooperation agreements were established between CleanSeaNet and operational institutions working closely with national maritime authorities in different regional seas, in order to promote the development of oil spill modelling services able to link to CleanSeaNet. A regional sea approach to oil spill modelling can take advantage of opportunities for cost efficiencies from sharing operational and maintenance costs of modelling. The technical interfaces developed for data exchange enable data on oil spills detected by satellite to be sent to the regional models and to be available in their systems, and for appropriate modelling results to be returned to CleanSeaNet. In addition, having a designated model per regional sea, or group of models per regional sea, could reduce the cost of developing, maintaining and operating a model by each EU coastal Member State separately.

In this context, two operational services were implemented, in the Baltic Sea (Seatrack Web – operated by Swedish Meteorological Hydrographic Institute) and more recently, in the North Sea (OSERIT – Oil Spill Evaluation and Response Integrated Tool – operated by Royal Belgian Institute for Natural Science). A demonstration in the

Mediterranean Sea (using MEDSLIK model – developed by Cyprus Centre for Oceanography - CYCOFOS) was also developed.

In a similar approach, the work presented in this paper is relative to an initial demonstration of the link between CleanSeaNet and MOHID oil spill modelling services (hereinafter called MOHID-CSN service) in the Atlantic Ocean – on Portuguese continental coast, and its neighbourhood regions in Spain - Andalucia and Galicia (see Figure 40).

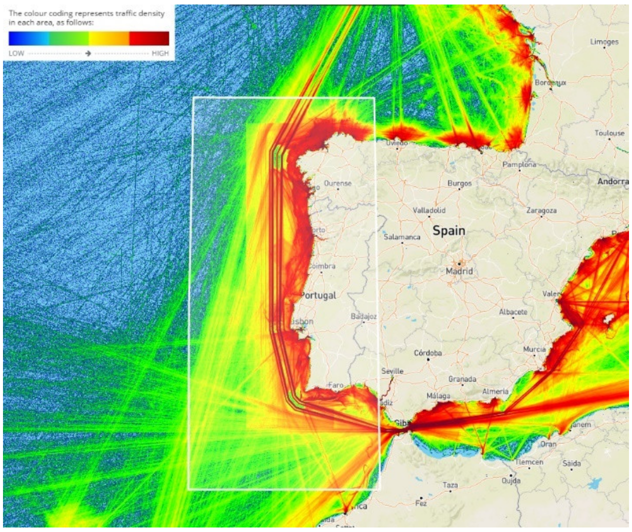


Figure 40 - Implemented area (white polygon) and shipping density in 2015 (distinct vessels on a daily basis and count positions / Km2. Blue: < 30; Green:30-70; Yellow: 70-140; Red: > 140 (MarineTraffic).

The MOHID-CSN service is a result of a close and fruitful cooperation between Portuguese Maritime Authority / Response Pollution Service (DGAM-SCPM), Action Modulers, MARETEC-IST (Marine, Environment & Technology Centre from Instituto Superior Técnico), EMSA, and Spanish Maritime Safety Agency (SASEMAR), in the context of multiple European projects implemented in the Atlantic region – ARCOPOL+ ("Improving maritime safety and pollution response through technology transfer, training & innovation"); ARCOPOLplatform ("Atlantic Regions Coastal Pollution Response"); (ARCOPOL project website; both projects funded by European Union INTERREG Atlantic programme), and presently, MARPOCS ("Multinational Response and Preparedness to Oil and Chemical Spills") - MARPOCS project website) and MARINER ("Enhancing HNS Preparedness through training and exercising". MARINER project website; both projects funded by DG-ECHO – Humanitarian Aid and Civil Protection from European Commission), always in cooperation with regional and national authorities.

The area of initial implementation is subject to strong coastal pressures in different aspects. The area has a strong economic dependence of the sea, manifested in the most diverse ways, whether it's fishing, leisure activities, water sports, coastal tourism, or employment associated with the sea economy. This coast is crossed by important international shipping routes with most of the maritime traffic circulating to and from Northern Europe (view Figure 40), increasing the responsibility in terms of safety of navigation as well as in preventing and combating marine pollution. Figure 41 shows the CleanSeaNet detected oil spills in the Portuguese Economic Exclusive Zone (EEZ) since the beginning of the service (2008) till September 2016 (approximately 500 spills). It is visible the high concentration of detections (black dots) in the Portuguese Coast, which reflects the dimension of the problem in this area. Some of these detections have been also reported from fishing vessels, or from land sources (e.g. emergency discharges from wastewater treatment plants), however no exact data exists about the number of shore-based spills.

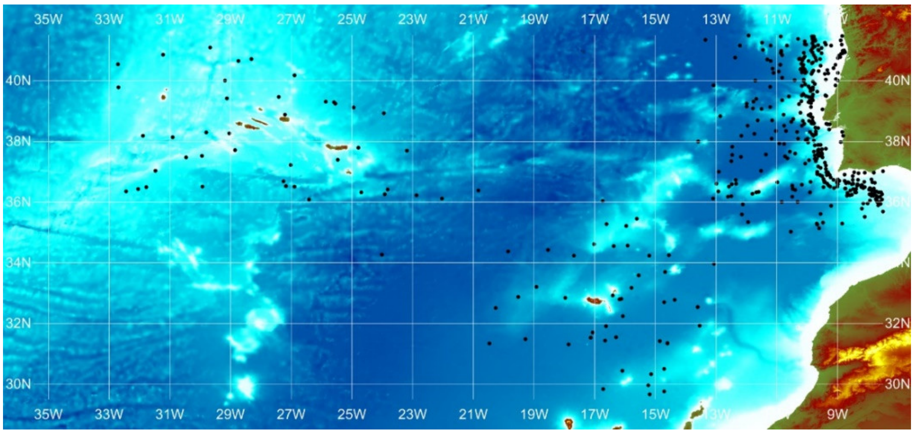


Figure 41 - CleanSeaNet detected oil spills (black dots) in Portuguese EEZ: 2008-2016 (DGAM-SCPM).

IV.1.2 Methods

IV.1.2.1 Conceptual Design

The development of automatic service-to-service (S2S) early warning spill forecasting systems (back and forth in time) connected to existing maritime surveillance automatic services in the referred areas of interest can be seen as a relevant effort to enhance preparedness and response mechanisms when facing oil spills, and contributing to the minimization and prevention of coastal contamination risks. If the developed systems are able to work with common, standardized, versatile and open-source technologies, the transferability of those operational systems to any other areas will be greater. Hence, the conceptual design adopted for the system here developed is totally based in the premise that it must be, as much as possible, transferable to any other geographical areas, possibly using any other remote sensing data sources, as well as other metocean modelling systems.

The development of a system with those conditions requires an open-source, versatile, reliable and efficient oil spill model, as well as an appropriate and scalable operational software framework capable of supporting and digesting multiple input data sources, from different data providers. Thus, the oil spill model adopted is MOHID, and the operational software framework used to manage the data is ACTION Server.

IV.1.2.2 Oil spill model

A lagrangian particle transport model (MOHID) is used to compute oil spills at sea in the automatic simulation of the trajectory of detected oil spills from CleanSeaNet service. The model simulates the trajectory forward and backward in time. In lagrangian models, simulated pollutants are represented by a cloud of discrete particles (or super-particles) advected by wind, currents and waves, and spread due to random turbulent diffusion or mechanical spreading.

The MOHID lagrangian module (Fernandes et al., 2013; Ascione Kenov, et al., 2014) can be run simultaneously with the hydrodynamic model (currents, water temperature, salinity, etc.), or in "offline" mode – the mode adopted in this work, for operational reasons. The model is able to digest currents, water properties, wave parameters and atmosphere properties from different model providers. Additionally, MOHID lagrangian module allows backtracking modelling, as well as a multi-solution approach (Fernandes et al., 2013) (generating computational grid on-the-fly, and using the available information from the multiple metocean forecasting solutions available). The user interaction with MOHID lagrangian module is presently available through many different web and desktop platforms (Fernandes et al., 2013), and the most recent is ACTION Seaport (ACTION Seaport Demo website); (Fernandes et al., 2016b).

The MOHID oil spill fate and behaviour model was initially developed in 2001 (Fernandes, 2001) and has been operationally applied in different incidents (Carracedo et al., 2006; Janeiro et al., 2014), field exercises and studies worldwide, allowing the simulation of major oil transport and weathering processes at sea. The source code of oil spill modelling system was recently updated to include full 3D movement of oil particles, wave-induced currents, and oil-shoreline interaction (Fernandes et al., 2013).

IV.1.2.3 ACTION Server

The central point of software framework developed is the operational software ACTION Server. This software works as the "heart" of the whole system, collecting, processing and storing all the input data (numerical models, remote sensing data from CleanSeaNet), interacting and operating MOHID, post-processing the information and then distributing the output data (including alerts and notifications).

ACTION Server is presently a plugin based, server system composed by a set of software components allowing to integrate and process different data sources and multiple numerical models. These software components can be installed as plugins, allowing the system to be scalable, depending on the end user needs. Several plugins are currently integrated to download data automatically from global, regional and local systems (e.g. NOAA GFS; CMEMS Global Forecast Solutions; MOHID, WW3, MM5, and WRF model outputs provided by MARETEC-IST and Meteogalicia; WW3 and SWAN models provided by Puertos del Estado; real time acquisition from the meteorological network Weather Underground).

This software is currently used in production mode as backbone for ACTION Modulers's flood early warning system (ACTION Flood), sea port operational support system (ACTION Seaport) and operational bathing water forecast system ACTION Beach (ACTION Beach description; ACTION Beach Romania).

IV.1.2.4 Metocean modelling conditions

The oil spill model simulations take into account forecasted environmental field conditions that can influence the fate and behaviour of oil at sea. In the initial implementation presented here, the MOHID-CSN EWS digests metocean forecasted parameters generated by validated numerical models developed by MARETEC-IST. Using ACTION Server, the integration with any other data sources (either implemented by default in ACTION Server, like GFS or CMEMS global forecasting system, or using any other external data provider) is possible and straightforward, as long as the operational model results are published online in a catalogue web server (e.g. FTP, HTTP, THREDDS / OPENDAP), and the model output files are stored in a typical numerical data format (netCDF or HDF).

Currents and water properties (sea surface temperature, sea surface salinity and suspended particulate matter) are obtained from hourly outputs from PCOMS-MOHID model (Mateus et al., 2012, Pinto et al., 2012). PCOMS (Portuguese Coastal Operational Modelling System) is a 3-D hydro-biogeochemical model of the Iberian western Atlantic region. Ocean boundary conditions are provided by the Mercator-Ocean PSY2V4 North Atlantic and by tidal levels computed by a 2-D version of MOHID (Neves, 2013; Ascione Kenov et al., 2014), forced by FES (Finite Element Solution) global tide model in the version FES2004, and running on a wider region. PCOMS has a horizontal resolution of 6.6 km and a vertical delineation of 50 layers with increasing resolution from the sea bottom upward, reaching 1 m at the surface (Ascione Kenov et al., 2014).

Atmospheric conditions (wind velocity, surface air temperature, atmospheric pressure and visibility) are obtained from the meteorological forecasting system IST-MM5, using MM5 model (Grell et al.1994) with a 9km spatial resolution. This operational model was initially implemented by Sousa, 2002, and updated in 2005 (Trancoso, 2012). This model is also used as atmospheric forcing of PCOMS-MOHID, and its outputs are also every hour.

The wave parameters (wave period, wave height, wave direction and wave length) are obtained from the Portuguese wave forecasting system implemented at MARETEC-IST, using the hourly outputs from WaveWatchIII model (Tolman, 2009) with a 5km spatial resolution, and wind forcing provided by Global Forecasting System (GFS) from the National Oceanic and Atmospheric Administration (NOAA), with a spatial resolution of 0.5° (Franz et al., 2014).

IV.1.2.5 System development

The system is continuously monitoring EMSA's FTP server where any CleanSeanet oil spill notification is stored. The oil spill notification is downloaded immediately, uncompressing it and checking the geographical area of the spill. Depending on the area, a different mailing list is used to disseminate the results (for instance, if the oil spill is in Spain, SASEMAR contacts are notified). The whole process between the CleanSeaNet notification stored at FTP Server, to the mail distribution, takes an average time of 5 to 10 minutes.

The operational system prepares then the model input data files, by a) changing the model configuration files, b) generating polygons for the oil slick positions in a MOHID-readable fashion, and c) fetching the needed metocean forecasts to properly simulate the oil spill forward (24 hours) and backward (24 hours) in time. The model simulations usually take less than 5 minutes (this value can be higher if the spill has multiple slicks).

After the end of the model run, post processing actions are taken to convert MOHID model results in multiple formats adequate to be distributed to the oil spill responders. Conversions include common GML / XML formats to be uploaded and readable in EMSA web GIS; a standardized numerical data format (netCDF) for the same purpose; and KML format - to be loaded directly in Google Earth. MOHID native formats are also provided, to allow end-users to directly open it in MOHID Studio desktop GIS.

The last stage of the process is the distribution / uploading of the model results in the multiple platforms: a) EMSA's FTP server; b) MOHID-CSN EWS central web server; c) email notification sent to the proper responders, with meta-data of the forecasted spill and hyperlinks to visualize results hosted in the central web server (Figure 42).

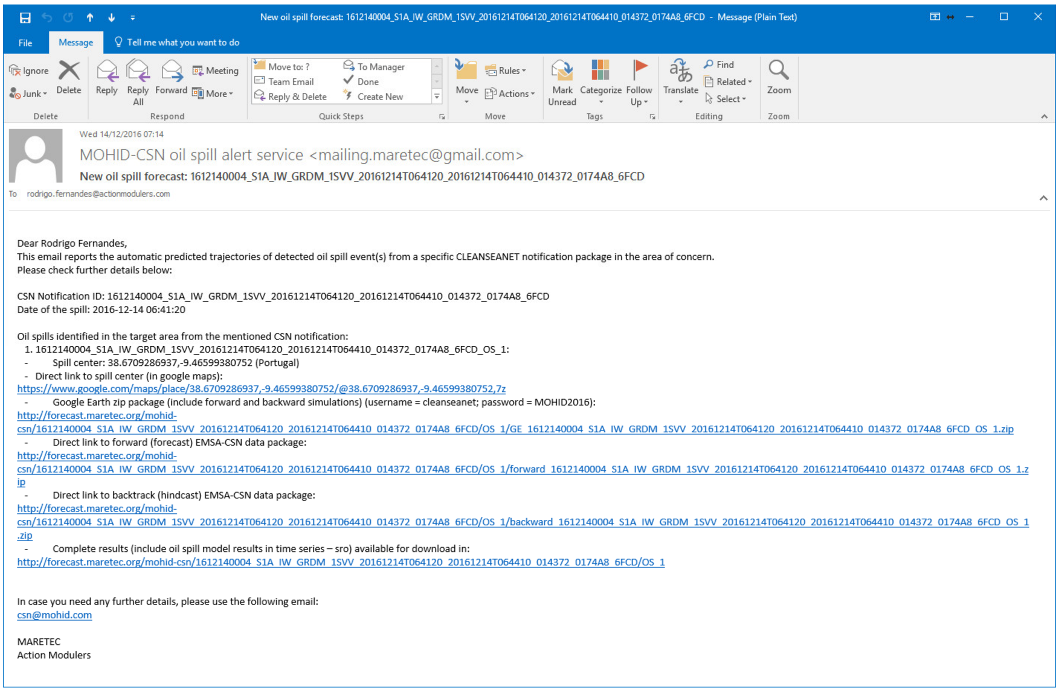


Figure 42 - Email generated by MOHID-CSN EWS with links to oil spill forecasts

Since no data is available related to the exact oil product, its weathering stage and if oil is present in the water column, different generic and common assumptions are taken in the configuration of the oil spill model. By default, a generic crude oil (API - American Petroleum Institute - gravity of 30, viscosity of 39 cP, oil-water interfacial tension of 20 dynes/cm) is assumed to be released on the surface exactly in the same polygon locations(s) as identified by CleanSeaNet. Each polygon is simulated independently. It is assumed that each identified polygon area corresponds to slick area from the end of the first spreading stage (gravity-inertial phase, that usually lasts only a few minutes; Fay, 1969). The volume or mass is then computed based on that assumption. It is assumed that the oil is fresh and all the typical oil transport and weathering processes are computed (mechanical spreading, evaporation, natural dispersion, emulsification, adsorption to sediments, dissolution, Stokes drift, turbulent diffusion, wind-driven velocity represented by 3% of the surface wind velocity). Assuming that most of the detected oil spills are vessel-borne and with oil products with a density lower than the seawater, it is considered that the initial oil slick is only present at surface (therefore, no initial oil is considered in the subsurface). An internal time step of 60 seconds is used in oil weathering computations; 120 seconds is the time step used in the computation of remaining lagrangian processes. A total of 500 particles are released in every polygon simulation, and the computational mesh used is composed of 500x500 orthogonal cells with 300m of spatial step, centred in the mass centre of the detected oil slick.

IV.1.3 Results

IV.1.3.1 MOHID-CSN EWS: Examples and performance

The MOHID-CSN EWS has been tested in operational mode since 15-4-2016, distributing notifications to SCPM-DGAM. During this test period, the system has already proven its usefulness on different occasions – mainly because the automatic system is able to generate near-realtime oil spill forecasts in user-friendly outputs (e.g. Google Earth), accelerating the usability of the model forecasts when compared to the traditional on-demand modelling systems used by response operators. The first example is related to an incident in the centre of Portugal, in 26-4-2016. SCPM-DGAM received the initial oil spill notification from CleanSeaNet at 19h47, relative to a supposed oil spill identified at 19h29 with 1.47 km^2, offshore of Aveiro. The MOHID-CSN EWS forecasts were duly distributed by email at 20h02 - in less than 15 minutes after initial CleanSeaNet notification (see Figure 43).

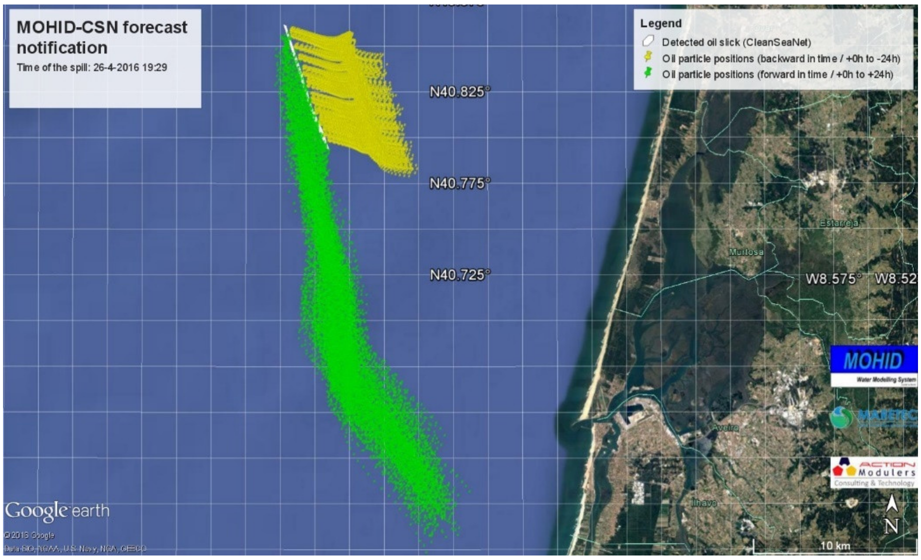


Figure 43 Integrated trajectory of oil spill simulated by MOHID-CSN EWS, in Google Earth

At 20:41, an email from MRCC (Maritime Rescue Coordination Centre), reported a correlation with the ship BITTEN THERESA (which had been questioned), and a drift forecast was requested by MRCC to the Hydrographic Institute (IH). At 23:22, IH sent the official forecast, with results similar to the MOHID-CSN notification. A response from the vessel was sent to MRCC at 26-4-2016 10h36, confirming that at 18h30, at the indicated location, tank cleaning had started, reporting that the last load was soybean oil.

In summary, the MOHID-CSN EWS forecasts were able to provide the fastest forecasts to this incident, with the results being comparable to the available on-demand forecasting systems. MOHID-CSN EWS was used as a first guess decision support system, allowing for faster identification of the potential polluter.

The second example is relative to an incident in 14-12-2016 (spill instant: 06:41), related to an operational / emergency discharge in a sensitive coastal area from a wastewater treatment plant (Guia outfall, in Tagus Mouth / Cascais), as a result of unusual water flow income due to pluvial waters in a strong raining event. In this case, the DGAM-SCPM was previously advised of the need for an emergency discharge, and was able to immediately prepare an observation team to follow the oil slick at sea. The MOHID-CSN EWS forecasts (see Figure 44) were duly distributed by email in less than 8 minutes after initial CleanSeaNet notification upload, and could be used by DGAM-SCPM to improve the tracking of the slick at sea (narrowing the search area), and to efficiently control if any nearshore resource would be potentially affected. Once the spillage happened (and slick detected), the main advantage here in relation to traditional on-demand systems is that the user wouldn't need any type of intervention to generate the result.

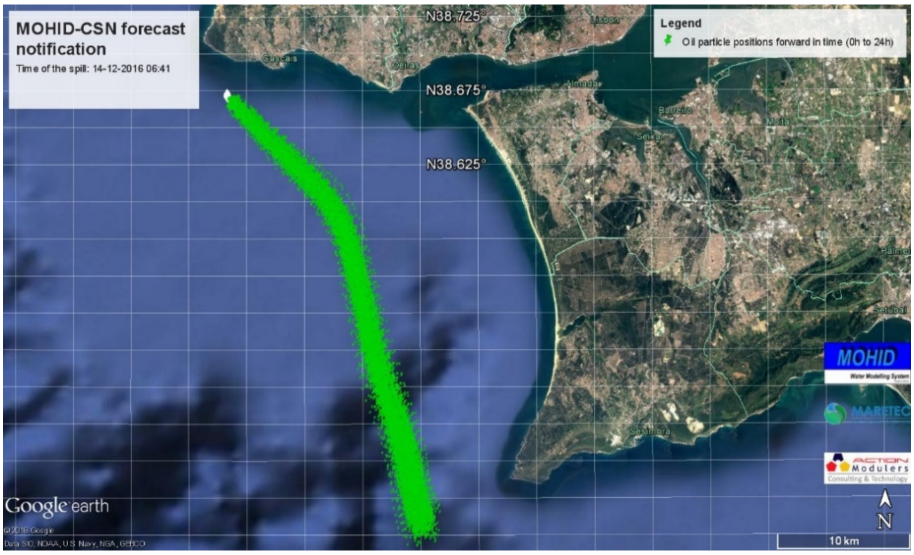


Figure 44 - Integrated trajectory of oil spill simulated by MOHID-CSN EWS, in Google Earth

At the present moment, the same system is currently being tested in operation mode for Andalusian and Galician regions (Spanish coastal regions in the vicinity of Portuguese continental coast), since 10-10-2016. During the testing period, corrections mainly related with operational modelling procedures and logistics are being performed (e.g. improvement of redundancy in terms of metocean forecasts; adjustment and optimization of the compromise between model domain sizes, computational time steps and precision of the results; correction of minor bugs when converting CleanSeaNet original polygons to MOHID model format, among others). As the oil spill detections are usually unpredictable and not so frequent, this testing and optimization phase is longer than the usual time involved in testing operational systems running in a daily-basis.

IV.1.3.2 Oil spill hazard analysis

The coupled MOHID-CSN system has also been applied in a historical analysis covering a long-term period (5 years between September 2011 and September 2016) for the Portuguese continental coast (i.e., using the oil spills detected in the Portuguese continental coast), with the aim of building a quantitative and representative oil spill hazard map of the Portuguese continental coast during the last 5 years. All the oil spills detected inside the area of study during the selected period (155 detected spills after filtering area and time period), were simulated in the same conditions as defined in the operational system (MOHID-CSN EWS) previously described. The geographical position and mass of all the lagrangian particles were recorded every hour and then integrated in time, allowing to obtain a single 5-year map representing the oil concentrations for the whole period. Higher concentrations represent greater probability of oil contamination. A seasonal comparison between spring + summer (21-March till 21-September) and autumn + winter (21-September till 21 of March) was also performed.

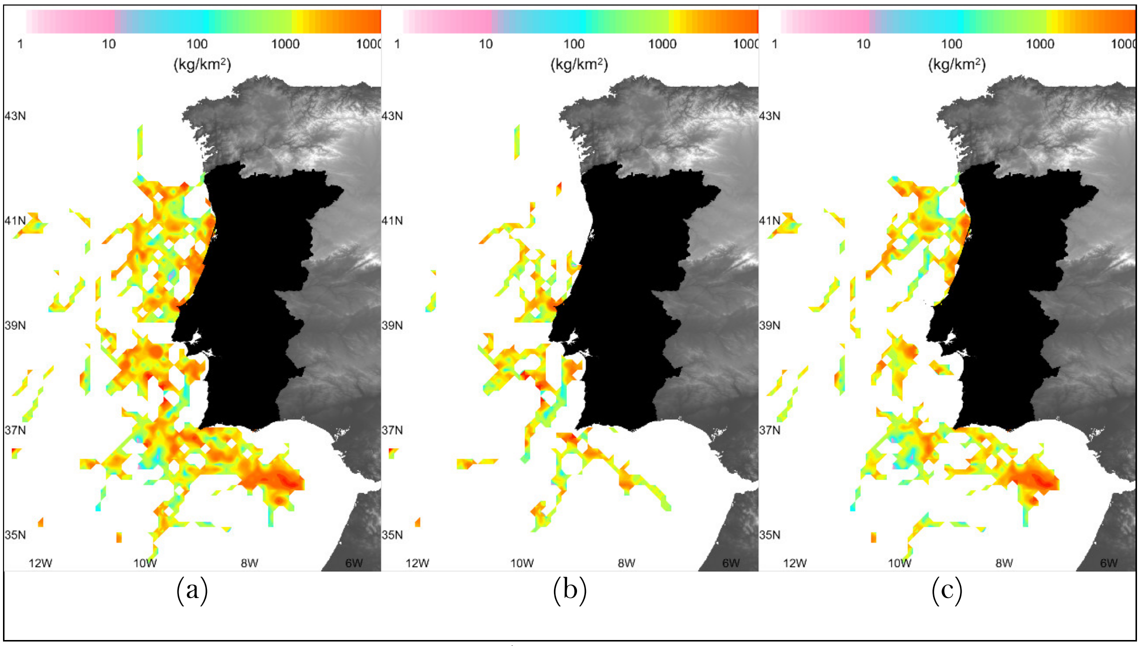


Figure 45 - Cumulative oil concentrations (kg/km2) in the Portuguese continental coast as a result from oil spill simulations from slicks detected by CleanSeaNet between 1-9-2011 and 1-9-2016; Left figure (a) represents the whole oil particles; figure in the centre (b) represents the oil particles in autumn and winter; right figure (c) represents the oil particles in spring and summer.

In the annual integration (Figure 45a), the pollution off the coast is demonstrated in the vicinity of the typical international shipping routes crossing Portuguese coast (Figure 40), particularly, near the Mediterranean Sea, in the boundary with Spain. Higher probabilities of nearshore contamination in the centre and north of Portugal is also registered. The southern boundary of Portugal (Algarve) is also identified as a “hotspot” location, but only in the western side, while the nearshore coast of Alentejo (west coast, in the south) has low probability of contamination – eventually due to a combination of the oil spill locations (usually far from the coast of Alentejo) and favourable metocean conditions along the year (offshore wind and currents). When analysing Figure 45b) and Figure 45c), higher probabilities of contamination can be found in summer, in a general way. Although specific reasons could not be clearly identified in the scope of this work, several hypotheses can be discussed (in the next section) and evaluated in further research work.

IV.1.4 Conclusions

The MOHID-CSN EWS developed and being operationally tested in an Atlantic region is in line with the EMSA strategy of contributing to the setting up, implementation and promotion of integrative decision support systems in EU Member States, supported by the intelligent combination of the existing surveillance capacity in EMSA (e.g. CleanSeaNet) with the regional and national operational metocean forecasting systems used by the national maritime authorities. The system here presented is now being distributed to Portuguese and Spanish National Maritime Authorities involved in oil pollution monitoring and surveillance. In the future, the system will be extended to other areas (and corresponding national or regional maritime authorities) in the Atlantic (Morocco, Canary Islands, Madeira Islands, and eventually other regions in Spain).

The MOHID-CSN EWS represents a step-up in the oil spill pollution preparedness & response in the Atlantic coast (handled by the corresponding maritime authorities in articulation with EMSA), proving its ability to reduce the time needed for the identification of the potential polluter (using backtracking modelling capacity), and being able to work as a credible first guess solution. Although not replacing the existing on-demand simulation tools, MOHID-CSN EWS works as an additional source of modelling information, contributing to the reduction of the uncertainties, inherent to the modelling activities.

From a developer point a view, since this operational system is all sustained by a set of flexible software tools (ACTION Server; MOHID oil spill model), there is a true potential of implementing this MOHID-CSN EWS in any region in EU (with CleanSeaNet covering the whole region) or worldwide, using different configurations and data sets: either using metocean forecasts from different data sources, or using other oil slick polygons detected by different Earth observation services (other than CleanSeaNet). This abstraction in relation to the data sets used represents an innovative and strategic development in terms of expanding the adopted methodology to any other areas. The implementation of this automated system using other kinds of software (e.g. using scripts and other oil spill model) is also potentially possible - as long these will not compromise the overall performance and reliability of the EWS.

The oil spill hazard mapping analysis raised some important issues that need to be addressed in future work. In terms of seasonal differences, hypotheses like false positives and illegal oil discharges from greater nearshore fishing activity in summer; false negatives and land-based emergency discharges from wastewater treatment plants in winter should be properly evaluated and studied. In addition, a comparison between this oil spill hazard mapping analysis based on oil slick detections, and a hazard mapping based only in vessel traffic routes could clarify some of the aspects identified in this work, for instance, a better identification of the relative weight of ship-borne pollution in the general vulnerability of oil spill contamination (i.e. if both methods for hazard mapping provide similar results, it means that ship-borne pollution must be the most important source of oil spill contamination).

Also, the verification of new techniques to detect oil spills with recently launched satellite SAR instruments (Copernicus Sentinel 1A / 1B), and the fusion of SAR data with high resolution ocean colour data (using for instance Copernicus Sentinel 3A) will contribute simultaneously to an even more efficient detection of oil spills and to the reduction of false detections.

V Shoreline holistic risk assessment of ship-based spills

V.1 Overview

This chapter is focussed in the design and conceptualization of a novel holistic vessel-based oil spill risk assessment model, and also in its testing, sensitivity analysis and application in the area of study.

The section V.2 consists on the description and implementation of a coastal sensitivity classification in the context of oil spills, for the Portuguese continental coast. This coastal sensitivity classification is an integral part of the risk model developed.

The development and testing of the risk model is explained in the previously published work included in section V.3, that describes the full concept and methodology behind the novel shoreline holistic risk mapping tool based in oil spills from vessels, as well as providing sensitivity analysis to evaluate the relative effect of some metocean parameters in the final results.

Finally, the last section (V.4) applies the risk model in the Portuguese continental coast providing a comprehensive risk assessment in the area of study, benefiting from the holistic risk tool developed above. This risk characterization includes not only an historic analysis to characterize the actual situation, but also a scenario risk assessment, based on expected evolutions and trends in global shipping industry (increasing sizes), or on climate change effects (e.g. decrease significant wave height).

V.2 Quantifying coastal sensitivity to oil spills for risk assessment purposes

Abstract

A proper knowledge, identification and quantification of the coastal sensitivity in the case of an oil spill incident is an important asset in the definition of contingency planning and risk assessment approaches, tactical response, and also in the definition of adequate environmental monitoring programmes. For instance, coastal sensitivity may help decision-makers in prioritization in the different stages of risk management: before, during and after a spill.

The work here presented includes the definition of methodologies for quantification of coastal sensitivity to oil spills, through the design of different coastal sensitivity indices applied in the Portuguese continental coast.

Three different sensitivity indices were considered: socio-economic index (related with the potential social and economic consequences); ecological index (related with potential damage to highly significant biological and ecological resources); and a coastal sensitivity index (related with the generic shoreline environmental sensitivity to oiling and easiness of clean-up and restore operations, mainly influenced by geomorphologic and morphodynamical aspects of the shore).

Along with desk work, based on aerial photos and on Google Earth, field surveys were conducted to define the coastal sensitivity index. The methodology was adopted from NOAA's ESI shoreline ranking. Socio-economic index was totally based on statistical information, mostly from official data sources. The methodology was adapted from previous work developed in the Iberian coast. Ecological index was based on identified networks of marine protected areas (RAMSAR, NATURA 2000).

The sensitivity indices obtained for the pilot area were defined with a very high spatial discretization, dividing the shoreline in multiple segments or stretches in extensions that can be as small as 200 meters, realistically representing the variability of the shoreline wherever information is available. The results are available on the web through Google Earth, and this directly imported to a dynamic risk assessment tool.

The adopted high level of spatial resolution improves the identification of the spatial heterogeneities in the coastal sensitivity and therefore provides uncommon and valuable baseline information able to help authorities in efficient risk management. For instance, when facing long shoreline contamination extensions, responders can prioritize clean-up operations in areas with greater sensitivity.

V.2.1 Introduction

Oil spills at sea are identified as one of the worst man-made hazards, representing important damage to marine ecosystems and public health, but also threatening local or even regional coastal economies somehow dependant on coastal activities, like tourism, fisheries, among others. The environmental impacts and socio-economic consequences can persist for several months or years, and some ecological resources or ecosystems may be irreversibly affected. When approaching and contacting the shoreline, the response and clean-up strategy can differ significantly, as a function of the type of the coastline – some types of coastline may be easier of harder to recover or to restore.

All those aspects are usually taken in consideration in risk management, and specifically, in the definition and quantification of risk levels. Risk quantification is rather important to support contingency planning or tactical response, even if only relative values are used (either compared in time, or in space). A valid and useful risk model to the decision-makers needs to consider not only the quantification of probability or hazard assessment aspects, but also the estimation of specific coastal sensitivity of the exposed areas.

Areas with high sensitivity and high probability of being affected by oil are considered more vulnerable than areas with low sensitivity and/or low probability of being affected. In this sense, the sensitivity maps should integrate information on environmental sensitivity to oil, obtained from the widest possible combination of environmental aspects, as geomorphological, chemical and physical characteristics and the biological, bathing, aesthetic and socio-economic responses (Castañedo et al., 2009).

One of the first methods to classify coastal sensitivity to oil spills was proposed by Gundlach and Hayes (1978). These authors classified coastal environments based on physical and geomorphological aspects. In 1979, United States National Oceanic and Atmospheric Administration (NOAA) introduced the Environmental Sensitivity Index (ESI) maps as an integral part of oil spill contingency planning and response. In 1989 these maps started to be distributed in digital formats using GIS techniques (Peterson et al., 2002). ESI maps still remains as one of the approaches most broadly used in the coast, estuaries and river environments, contributing to reduce environmental damages and clean-up efforts in the sequence of oil spills. ESI maps compile a set of key features such as a shoreline geomorphology sensitivity rank to oiling, and biological and human-use at-risk resources.

During the 2000's, and after that, new and improved approaches appeared worldwide, structuring oil spill sensitivity into three main layers, based on physical, biological and socio-economical dimensions related to the coast, and using quantitative approaches. In 2004-2007 period, in the aftermath of Prestige oil spill incident, one of the first methodologies integrating not only ESI index classification, but also a socio-economic index, was developed in the scope of EROCIPS project – those indices were integrated in the Portuguese Coastal Atlas, which was released online for the public in Google Earth format, and also included images of the different shoreline segments all around the Portuguese continental coast (MARETEC, 2007). Although this work has established an ultra-refined discretization of the Portuguese coastline based on the ESI classification, measured with a thorough field work, this work lacked in objectivity associated to the methodology applied to the socio-economic index.

In 2009, some approaches using 3 main layers could be found for instance in Castañedo et al., 2009 – applied to the Cantabrian coast in Spain. Santos and Andrade, 2009 and later in Santos et al., 2013 – applied a methodology to the Portuguese mainland, involving 2 main dimensions – socioeconomic and ecological (with this one including shoreline type and protection and conservation areas). This work resulted in a classification divided by municipalities, which may not reflect the heterogeneity of the coastline. Leal, 2011 proposed a new quantitative approach, applied for the southwest Algarve coastal area, considering not 3, but 4 groups for coastal sensitivity: the relevance of the recreational bathing waters, ecological relevance, type of coastline, and accessibility to the coastline. This methodology is particularly interesting for coastal areas with high interest from a recreational point of view. Finally, in 2013, Oliveira et al., 2013, reviewed the previous methodologies and proposed a new one, very detailed and applied to the coastal lagoon in Portugal (Ria de Aveiro).

The main objective of this work is to design and implement an adequate quantitative methodology for coastal sensitivity in the Portuguese continental coast, mainly supported by objective parameters, and based on previous research and field work, and common methodologies already developed in the area of study, when and wherever possible.

The area of study (Portuguese continental coast) is a highly sensitive area in multiple physical, biological and socio-economic aspects, and at the same time, highly exposed to potential oil spill contamination incidents, mainly due to heavy maritime traffic along the coast. Although increased safety in shipping industry (e.g. double hull) and coastal surveillance mechanisms (e.g. VTS, AIS, EMSA's CLEANSEANET system) allow to mitigate the risk in the Portuguese coast, the increasing seaport activities, shipborne trade, ship traffic and size of the vessels contribute to increasing concerns in terms of contamination incidents.

The evolution of the economy in Portugal, more and more related to coastal tourism and sea economy, and with most of the population living close to the sea, increases the pressure on the existing environmental and biological coastal resources.

V.2.2 Generic approach and methodology

Based on the work previously done in EROCIPS in terms of the segmentation of the Portuguese coastline and the corresponding coastal sensitivity index; and integrating the methodologies generated in the meanwhile as described in the section above, a new method was proposed for the classification of the coastal sensitivity.

Coastal sensitivity was divided in 3 different indices: coastal sensitivity index (*CSI*), socio-economic index (*SESI*) and ecological index (*ECSI*).

Those indices were then integrated and made available in digital format, on the web through Google Earth (Action Modulers, 2017).

The construction of those indices was based on the combination of aerial photos, Google Earth images, field surveys in the shoreline, statistical data and bibliographic reviews.

The obtained sensitivity indices were usually defined with a high spatial discretization, dividing the shoreline in multiple coastline segments (or stretches) in variable lengths that can be as small as 200 meters, realistically representing the variability of the shoreline. The Portuguese continental coast was divided in more than 1000 segments, with an average segment length of 1230m, and a median length of 435m.

The coastline was initially divided into segments according to the CSI variability / heterogeneity, which is assumed to be the most important sensitivity index in terms of risk analysis and response to oil spills. The other indices (SESI and ECSI) followed exactly the same segment division defined in CSI. Thus, some multiple consecutive segments have the same values for SESI and ECSI. The adoption of common segment divisions for all the indices is important, because this segmentation will be also used to characterize / the risk indices (a risk value will be computed by segment).

Each of the coastal sensitivity indices have a classification ranking (CSI - 1 to 10; SESI - 1 to 5; ECSI – 1 to 5). Higher values mean always higher sensitivity to oil or chemical spills. For instance, a value of 10 in CSI means that the coastline will be extremely sensitive and difficult to clean.

In the next chapters, more information about each one of the coastal sensitivity indices is provided.

V.2.3 Coastal sensitivity index (CSI)

This index (*CSI*) represents the quantification of the valuation of the environmental sensitivity (ecological, landscape) of the areas of the maritime coast and/or the surrounding waters that can be reached by sea pollution from hydrocarbons and/or other dangerous substances spills.

For the general group of areas of the maritime coast, NOAA's ESI (Environmental Sensitivity Index) ranking (NOAA, 2017) was adopted. The ranking of this index, which varies between 1 and 10, coincides with the scale of the NOAA's ESI (Petersen et al., 2002), defined to characterize zones of the shoreline in function of the following parameters:

- Exposure to wave and tidal energy
- Slope of the coast (intertidal zone)
- Type of substrate (size, permeability and mobility)
- Biological productivity and sensitivity
- Ease clean-up

The colours used to visualize the *CSI* ranking are the same as used in NOAA's ESI (see next table).

Table 4 - Classes used for costal sensitivity index (CSI)

Colour	*CSI*	Colour code (RGB)			*CSI* and type of shoreline
		R	G	B	
	1	119	38	105	1A: exposed rocky shores 1B: Exposed, solid man-made structures
	2	174	153	191	Exposed Wave-cut Platform in Bedrock, Mud, or Clay. Medium slope
	3	0	151	212	Exposed fine to medium-grained sand dissipative beaches
	4	146	209	241	Exposed beaches with coarse grained or fine to medium-grained sand; sheltered beaches with fine grained sand
	5	152	206	201	Mixed sand and gravel beaches
	6	0	149	32	6A: Gravel beaches 6 B: Riprap
	7	214	186	0	Exposed tidal flats
	8	225	232	0	8A: Sheltered scarps in bedrock, mud or clay 8B: Sheltered, solid man-made structures
	9	248	163	0	9A: Sheltered tidal flats 9B: Sheltered low banks
	10	214	0	24	Salt and brackish waters marsh, freshwater marshes, swamps, mangroves or scrub wetlands

A rank of 1 represents shorelines with the least susceptibility to damage by oiling. Examples include steep, exposed rocky cliffs and banks. The oil cannot penetrate into the rock and will be washed off quickly by the waves and tides.

A rank of 10 represents shorelines most likely to be damaged by oiling. Examples include protected, vegetated wetlands, such as mangrove swamps and saltwater marshes. Oil in these areas will remain for a long period of time, penetrate deeply into the substrate, and inflict damage to many kinds of plants and animals.

In regions like coastal shoreline (restricted) waters, commercial ports, and all-purpose terminals, fishing ports, marinas or yacht harbours, and unrestricted waters, *CSI* is invariable and considered to be 6.

As a reference, in Continental Portugal, the CSI values obtained vary from a range of 1 to 10, with an average value of 4.1 and a median value of 3, which means that the most common type of coastline in Portuguese continental territory is "exposed fine to medium-grained sand dissipative beaches". The next image shows a zoom of CSI in the Tagus estuary.

Figure 46 - Coastal Sensitivity Index in the Tagus Estuary

V.2.4 Socio-economic sensitivity index

This index (*SESI*) intends to reflect the social-economic relative importance to the populations of the exploitation of the coastal zone under analysis (e.g. a beach not often used, or used but without significant infrastructures, and/or a beach with important economic value - restaurants, etc.). While the coastal sensitivity index *CSI* already considers the normal habitats for that shoreline, it does not consider other improvements that can exist in the zone and that are not specific of the characterization of index *CSI*, as fisheries or aquaculture, that have to be considered through the social-economic index *SESI*. This index varies from 1 to 5.

The determination of the SESI absolute values previously mentioned (1-5) was a result of the consideration of different socio-economic groups assuming different relative weights to each one. The relative weight of each group was based on different references (Leal, 2011; Castañedo et al., 2009; Santos et al., 2013). It was assumed that the local population that lives in coastal parishes is the most important factor, with a relative weight of 50% (Santos et al., 2013 uses 60%). The relative weights from the remainder groups (fisheries and aquaculture, tourism, and recreational activities) are mainly based on the work proposed by Castañedo et al., 2009 – which takes in consideration the impact degree and the recovery time from past accidents as multiplying factors. Although Castañedo et al. 2009, separated the fisheries from the aquaculture, in this revision aquaculture was considered as an integrative part of fisheries (due to lack of detailed statistical data from aquaculture activities), and therefore the impact degree and recovery time adopted was based on the values obtained from Castañedo et al., 2009 for the fisheries only. The next table reflects the relative weights used in the socioeconomic index, according to the different socioeconomic groups.

Table 5 - relative weights from the different groups used in the socioeconomic index

	Tourism	Fisheries / aquaculture	Recreational activities	Population
Impact degree Id (%)	10	100	100	n/a
Recovery time Rt (months)	6	4	0.25	
Weight (Id x Rt)	60	400	25	
Relative weight in socioeconomic index (%)	**6.18%**	**41.24%**	**2.58%**	**50%**

Each group is composed by one or more statistical indicators. Since all of them have different units, they are normalized to an identical interval following a min – max approach, therefore converted to a scale between 0 and 1 (Santos et al., 2013):

$$\frac{(x-\min)}{max-min} \qquad (1)$$

After applying all the previous calculations considering Table 5, the obtained integrated value for each segment is also normalized between 0 and 5:

$$\frac{5(x-\min)}{max-min} \qquad (2)$$

And finally, the numerical value is rounded up, resulting in a value between 1 and 5.

In order to take into account the local importance of different activities like fisheries or tourism, some used indicators were divided by the number of municipal inhabitants (and converted to /1000 inhabitants unit). This procedure allowed to minimize biased values in certain places, simply because the population is too low or too high (e.g. in terms of fisheries sensitivity, without this procedure, a coastal segment in an area with 1000 inhabitants where 50 of them are fishermen, would be significantly less important than a segment from an area with 100 000 inhabitants with 100 fishermen, which is not considered correct).

Some coastal segments include more than one parish, municipality or region. In those cases, an average was determined for all the indicators.

Next, the different groups for computing the SESI are described in detail:

V.2.4.1 Population

This group characterizes the population that lives in coastal parishes (LAU 2 – local administrative unit), as used by Santos et al., 2013. Therefore, only one indicator was considered in this group, and was obtained from Portuguese Statistical National Institute - INE, gathered in *Censos* 2011 (INE, 2017).

V.2.4.2 Tourism

Tourism was characterized also by a single indicator, which was the number of bed accommodations / 1000 inhabitants, for the associated municipality. Geographical data was obtained from INE, 2015 (data from 2014).

V.2.4.3 Fisheries and aquaculture

The determination of fisheries, aquaculture and saliculture sensitivity to oil spills was obtained by the weighted combination of three different indicators (data obtained from INE, 2015 (data from 2014)):

- Number of fishermen registered in the associated port / 1000 inhabitants (relative weight = 40%).
- Fish captured and unloaded in the port (in €) / 1000 inhabitants in the associated (relative weight = 40%).
- Aquaculture and saliculture production in the associated NUTS 2 region (in €) / 1000 inhabitants (relative weight = 20%)

V.2.4.4 Recreational activities

Two different items were considered (with equal relative weight) for characterizing the sensitivity to recreational activities:

- Number of marina berths or moorings for recreational vessels / 1000 inhabitants in the associated municipality (relative weight = 50%). (DGRM, 2015)
- Index of bathing waters importance (relative weight = 50%)

The determination of index of bathing waters importance was obtained from the combination of other three indicators, using an equal proportion for each of them (relative weight = 33.3%):

- existence of blue flag in the coastline segment (0/1)
- existence of beach concession in the coastline segment (0/1)

- aptitude for nautical sports in the coastline segment (0/1)

The information regarding the existence of blue flags attributed in 2015 was obtained from the European Blue Flag Association in the Portuguese website (ABAE, 2015)

Beach concession information was obtained from Portuguese Environmental Agency, in their specific bathing water GIS website (APA, 2015).

The information about nautical sports aptitude in the coastline segments is found in the website "wannaSurf" (wannaSurf, 2015), following the approach used by Leal, 2011.

The *SESI* final values obtained vary from a range of 1 to 5, with an average value of 2.3 and a median value of 2.

Figure 47 – Socio-economic sensitivity index in the south of Portugal, represented by different colours. Blue = 1; Green = 2; Yellow = 3; Orange = 4; Red = 5

A universe of 32 segments were found to have a ranking value of 5. Most of them are localized in Algarve (Portimão), Setúbal, Lisbon (Cabo Ruivo, Parque das Nações) and Peniche.

The high socio-economic values in Lisbon are related to the fact that the population density is very high in that region. Although population density is low in Peniche, the economy strongly depends on coastal recreational activities like surf (the highest value for recreational activities is precisely in this municipality), fisheries (which assumes the highest importance here), and also some aquaculture industry. Portimão has high population density, and the highest sensitivity to aquaculture at a national level. All of the previous regions have significant tourism industry (although the highest sensitivity in this group is recorded in Albufeira municipality, which doesn't have shoreline segments with SESI above 4).

The identified segments in Setúbal are not highly sensitive to tourism group, nevertheless, the population density assumes the highest values in Portugal, and since this group represents 50% of the relative weight in SESI, some shoreline segments in this municipality assume particular sensitivity.

The next table shows the top-14 identified segments with highest values, ordered by the SESI prior to the round-up procedure.

Table 6 – Ranking (top-14) of socioeconomic sensitivity indices in the continental Portuguese coast.

SESI	Shoreline segment	SESI	Shoreline segment
5	Praia da Rocha (Portimão)	4.37	Praia a nordeste da tomada de água (Setúbal)
4.96	Praia do Vau (Portimão)	4.37	Interior da Doca do Comércio (Setúbal)
4.89	Foz do Arade (Portimão)	4.37	Doca do Comércio (Setúbal)
4.89	Foz do Arade 1 (Portimão)	4.37	Doca do Comércio 1 (Setúbal)
4.89	Praia do Vau à Praia da Rocha 1 (Portimão)	4.37	Doca do Comércio 2 (Setúbal)
4.89	Praia do Vau à Praia da Rocha 2 (Portimão)	4.37	A sul da Doca do Comércio 1 (Setúbal)
4.37	Molhe na tomada de água 1 (Setúbal)	4.37	A sul da Doca do Comércio 2 (Setúbal)

V.2.5 Ecological sensitivity index

The ecological sensitivity index (*ECSI*) (or biological sensitivity index) was ranked according to special protected areas from the National Network of Protected Areas (ICNF); e.g. special habitats - NATURA 2000 (European Environment Agency, 2017), natural parks, natural reserves), RAMSAR areas (wetlands; RAMSAR Convention Secretariat, 2017), and UNESCO's Biosphere Reserve (UNESCO, 2017). None of these ecological classifications are included in the Coastal Sensitivity Index, thus, avoiding redundancy. This index varies from 1 to 5, being 5 the most sensitive (see next table).

Table 7 - Classes used for ecological sensitivity index (ECSI)

ECSI Ranking	
1	No special protected area / Unprotected
2	Protected Landspace
3	Natural Monument / Natural Reserve
4	Natural Park/ National Park
5	Natura2000 / RAMSAR / UNESCO Biosphere Reserve (RB)

The shoreline segments were once again defined as the same as used for Coastal sensitivity index (CSI). The average ECSI value is 3, although most of the segments are indeed classified 1 (514 shoreline segments) or 5 (508 shoreline segments). The median value is 2. In the next picture the predominance of values 1 and 5 can be seen.

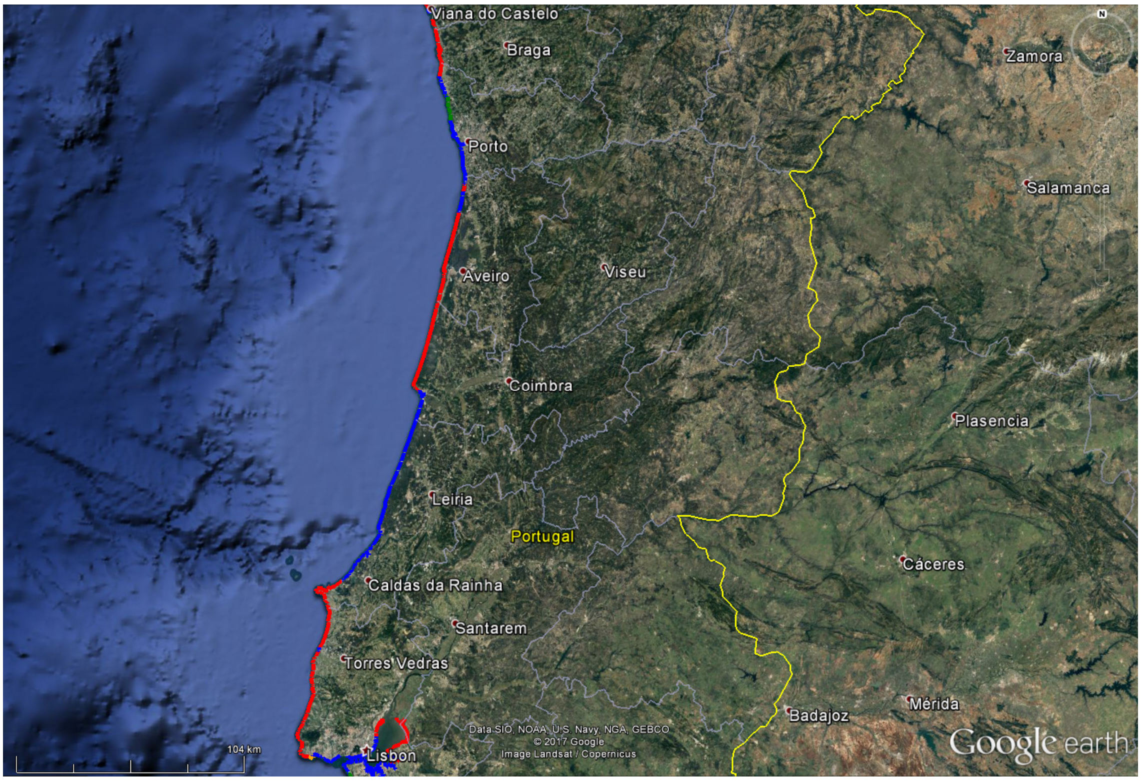


Figure 48- Ecological sensitivity index in the North of Portugal, represented by a using a colour scale: blue = 1; green = 2; yellow = 3; orange = 4; red = 5.

V.2.6 Final remarks

The scope of the work here presented was mainly the establishment and application of a standardized procedure for ranking the studied area in terms of coastal sensitivity. These ranked indices are relevant to a proper prioritization in terms of contingency planning, tactical response strategies, and risk assessment. The adoption of a high level of spatial resolution for the coastal sensitivity indices represents an important and efficient support to responders prioritizing their resources and clean-up operations in areas with greater sensitivity.

Other detailed and qualitative parameters may and should be considered to complement the information collected (e.g., NOAA collects information from several other parameters for the environmental sensitivity index – Petersen et al., 2002).

The classification method adopted is in line with other coastal sensitivity classifications that have been established in other regions and countries (e.g. Spain).

This methodology can be easily extended to other regions in Portugal (e.g. Madeira and Azores; indeed, in the course of this work, the adopted methodology has been implemented in Madeira island, in the scope of MARPOCS project - funded by DG-ECHO under agreement ECHO/SUB/2015/713854/PREP08), as well as in other countries. Some adaptations though may need to be made, in order to accommodate each country specificity, mainly in terms of the classification of environmentally protected areas (for the ecological index), or statistical information in terms of socioeconomic data (for the socioeconomic index).

The results obtained seem to geographically reflect what would be expected for the continental Portuguese territory. The socioeconomic sensitivity index, which is the most complex, reflects values that are in agreement to what would be expected.

The 3 indices were defined in different time periods. It must be taken in consideration that these indices were assumed to be constant, although some of the conditions considered may change and evolve in time, in two different time scales:

a) Annual or cyclical changes – cyclical behaviour like tidal regimes, movement of tourists and population during summer vs. other seasons, the seasonal behaviour of fauna and flora, may contribute to seasonal variations in all the indices.
b) Continuous or disruptive changes – climate change, coastal erosion, new infrastructures and other geographical evolution may change the indices.

Thus, in the future, these indices should be dynamic and change along each year, to answer the previously described cyclical changes.

In addition, maintenance and revision processes should be duly pursued, in order to consider the continuous and disruptive changes, allowing to reflect the actual coastal sensitivity.

V.2.7 Acknowledgments

The coastal sensitivity index was initially obtained in a joint collaboration between MARETEC-IST, CIIMAR and Hidromod, funded by project EROCIPS (INTERREG IIIb Atlantic Area). The socio-economic sensitivity index was designed, implemented and funded by ARCOPOL Platform (2013-1/252; EU Atlantic Area).

V.3 Combining operational models and data into a dynamic vessel risk assessment tool for coastal regions

Abstract

The technological evolution in terms of computational capacity, data acquisition systems, numerical modelling and operational oceanography is supplying opportunities for designing and building holistic approaches and complex tools for newer and more efficient management (planning, prevention and response) of coastal water pollution risk events.

A combined methodology to dynamically estimate time and space variable individual vessel accident risk levels and shoreline contamination risk from ships has been developed, integrating numerical metocean forecasts and oil spill simulations with vessel tracking automatic identification systems (AIS). The risk rating combines the likelihood of an oil spill occurring from a vessel navigating in a study area – Portuguese Continental shelf - with the assessed consequences to the shoreline. The spill likelihood is based on dynamic marine weather conditions and statistical information from previous accidents. The shoreline consequences reflect the virtual spilled oil amount reaching shoreline and its environmental and socio-economic vulnerabilities. The oil reaching shoreline is quantified with an oil spill fate and behaviour model running multiple virtual spills from vessels along time, or as an alternative, a correction factor based on vessel distance from coast. Shoreline risks can be computed in real-time or from previously obtained data.

Results show the ability of the proposed methodology to estimate the risk properly sensitive to dynamic metocean conditions and to oil transport behaviour. The integration of meteo-oceanic + oil spill models with coastal vulnerability and AIS data in the quantification of risk enhances the maritime situational awareness and the decision support model, providing a more realistic approach in the assessment of shoreline impacts. The risk assessment from historical data can help finding typical risk patterns, "hot spots" or developing sensitivity analysis to specific conditions, whereas real time risk levels can be used in the prioritization of individual ships, geographical areas, strategic tug positioning and implementation of dynamic risk-based vessel traffic monitoring.

V.3.1 Introduction

The maritime surveillance systems are becoming more effective and developed for coastal regions (e.g. terrestrial and satellite-based Automatic Identification System – AIS, UAVs), and the maritime security rules are becoming more restrictive, following MARPOL convention (e.g. shift to ships with double hull). However, the increasing global ship traffic (four times as many ships now than in 1992 – Tournadre, 2014) and maritime transport of oil products (ITOPF, 2015) make it more difficult to significantly reduce the environmental, economic and social risks posed by potential spills. Additionally, the use of increasingly larger vessels (up to 100,000–150,000 tonnes) means that if a major accident takes place, the amount of oil released could be vast.

In fact, the environmental and socio-economic issues associated to spills is and will always be a main topic: spill events are continuously happening, most of them unknown for the general public because of their small-scale impact – for instance, half of the total oil spills in the marine environment come from operative discharges by shipping and in most of these cases the discharges are illegal (GESAMP 2007). Nevertheless, some oil spills become authentic media phenomena in this information era, due to their large dimensions and environmental and social-economic impacts on ecosystems and local communities, and also due to some spectacular or shocking pictures generated (Leschine, 2002).

Consequently, the planning and prevention in the management of spill incidents at sea is extremely important in the reduction and minimization of potential impacts. Latest scientific and technological developments on coastal monitoring and operational oceanography have provided the opportunity to build more complex and integrated decision support systems for coastal risk management. The increasing operational predictive capacity of marine weather conditions (Hurlburt, et al., 2009; Schiller, 2011) and better knowledge in fate and behaviour processes of pollutants spilt at sea or costal zones (Fingas, 2015; Johansen et al., 2015; Zhao et al., 2014a; 2014b; Gong et al., 2014), together with the presence of advanced surveillance monitoring tools (Fischer and Bauer, 2010), can be integrated in order to provide a safer support for decision-making in emergency or planning issues associated to pollution risks.

The development of risk assessment studies has been used for multiple purposes, including contingency planning for response and preparedness, developing spill prevention measures, or evaluating oil exploration sites, etc. (Etkin, 2014).

Along the years, innovative oil spill hazard or risk assessment studies in coastal and marine environments have been published, considering historical data, reference situations, and typical or extreme scenarios (Castañedo et al., 2009; den Boer et al., 2014; Otero et al., 2014; WSP Canada Inc., 2014; Liubartseva et al., 2015), revealing their vocation for supporting contingency planning and strategic decision making. Silveira et al., 2013 developed also a new method to calculate the ship risk collision, applied in the Portuguese continental shelf with AIS data, but without connection to oil spill hazard assessment or taking into consideration metocean conditions. Nevertheless, none of the previous studies were developed and applied in real-time risk assessment.

Other studies and methodologies developed dynamic approaches, with the possibility of being used in real-time support - Grifoll et al, 2010; Eide et al, 2007a; 2007b; Bi and Si 2012; Olita et al., 2012; Goldman et al., 2015; Canu et al., 2015. However, the method proposed by Grifoll et al, 2010 doesn't include a fate and behaviour oil spill model for a better determination of areas affected by oil. The work developed by Eide et al, 2007a and 2007b included an oil spill model, however the simulations were previously obtained, based on typical scenarios, and without considering the dynamic changing of environmental conditions. Bi and Si 2012 also presented a novel method for dynamic risk assessment of oil spill accidents based on numerical simulation, but in this case the method is only applied to on-demand spill event or scenario, instead of providing continuous risk mapping based on ship traffic. Olita et al., 2012; Canu et al., 2015; Goldman et al., 2015 don't integrate directly metocean modelling data in the risk (accident probability) model, and the latter two papers don't use vessel data.

In this work, we present an innovative and holistic methodology for dynamic shoreline risk quantification, with full integration of numerical metocean forecasts and oil spill simulations with the existing monitoring tools (AIS), and with the possibility of being used to study past periods, projected scenarios and also supporting continuous monitoring, contributing to real-time maritime situational awareness. The main purpose is to build a decision support system capable of quantifying time and space variable shoreline pollution risk levels, coming from ships along the coast, and combining multiple information layers:

a) instant vessel information (AIS)
b) regional statistics information on vessels accidents history, coastal vulnerabilities

c) instant metocean forecasting data,
d) continuously simulated oil spill fate and behaviour from ships along the coast.

The development of a risk assessment approach integrating economic, environmental and social aspects combined with operational oceanography and available surveillance monitoring systems is in line with the blue growth paradigm, resulting in an innovative, holistic and sustainable approach for the maritime sector.

The relevance of integrating the oil spill model and metocean data from forecasting systems in the risk algorithm is evaluated on a study area described in the next section.

V.3.2 Materials and methods

V.3.2.1 Pilot area

The whole system has been implemented and tested in the Portuguese continental shelf. This peripheral area is a high shipping density zone (more than 55000 commercial vessels per year crossing this area, and an average number of 600 ships of all types present in the studied area, according to MarineTraffic, 2015) with a complex network of routes, being an obligatory passage point between the Mediterranean Sea and Northern Europe or American Continent (Silveira et al., 2013) (see **Error! Reference source not found.**).

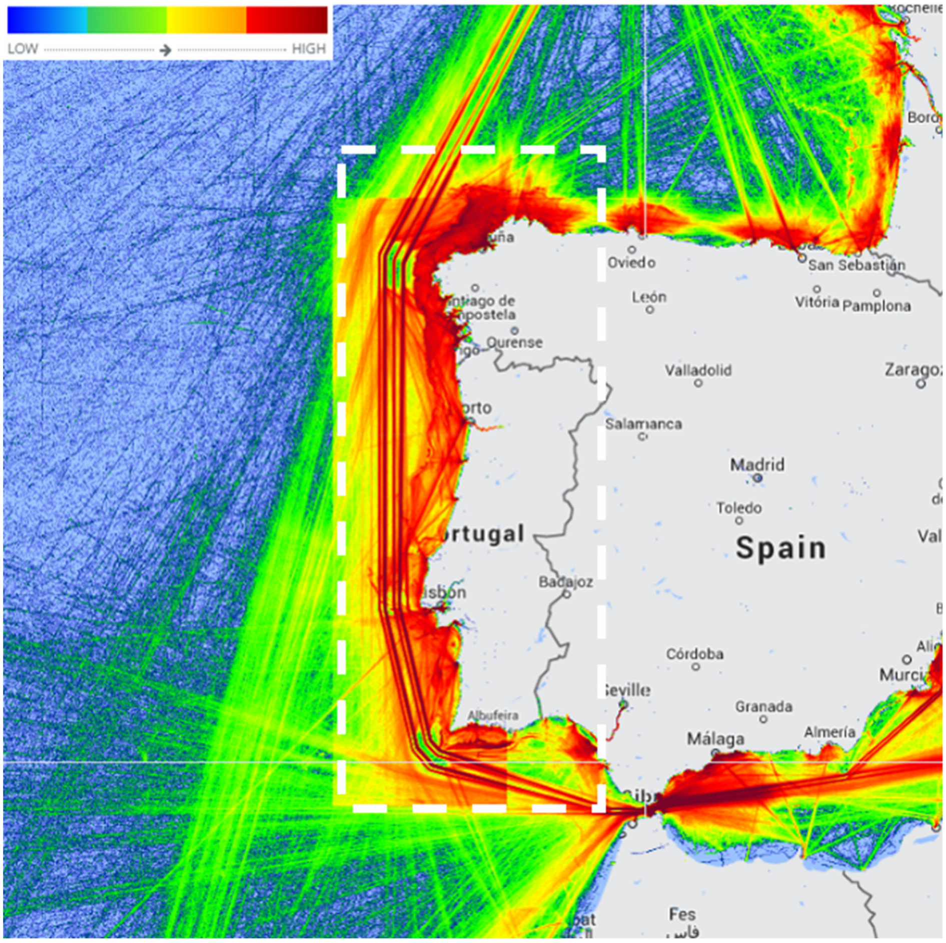


Figure 49 - Ship density map around the pilot area in 2014. The white rectangle represents the area considered in this work to study the shoreline contamination risk in the Portuguese continental coast (source: marinetraffic.com).

In this geographical zone, the activities in the near-shore area assume a very relevant role in the social, environmental and economic context (vast potential in natural resources, fishing, aquaculture, maritime commerce and port activity, leisure, sports and tourism activities).

In Portugal, the direct contribution of the maritime economy amounted to about 2.5% of national gross value added in 2010 and 2.3% of national employment (DGPM, 2012). Tourism, on the other hand, is gaining an important weight in the economy and is currently representing 48% of the total employment related to maritime activities (DGPM, 2012), as the country is widely known as a sun and beach destination within Europe counting with a wide accommodation and restoration infrastructure.

The high frequency of ships navigating in the Portuguese coast, together with the Portuguese dependency on the economy of the sea and natural resources, raise the awareness for the risk of water pollution events in this area.

V.3.2.2 Approach

The method proposed for quantification of risk combines the likelihood of an oil spill occurring from a vessel navigating in the study area with the assessed consequences to the shoreline, where risk is the product of the probability (or frequency) of oil spill accidents from maritime traffic, times the severity (or consequences) of the events:

$$Risk = Probability \times Severity \tag{10}$$

Governed by the previous expression, different types or risk levels are determined:

- the individual risk of oil spill accident for each vessel, depending on the vessel itself and on the metocean conditions, which is not dependent on the coastal consequences
- the risk of shoreline contamination taking in account coastal vulnerability indices with the integration of the above risks of oil spill accidents of all the vessels present in the vicinity of a given coastal stretch. To account for the potential consequences and amount of oil reaching shoreline, two strategies are implemented and evaluated:
    - a modelled one using an oil spill transport and behaviour spill modelling for each vessel
    - a non-modelled one based on a correction factor function of the distance between the vessel and the coast stretch.

The methodology and some of the statistical data is based on the risk assessment produced for Portugal and Galicia in the scope of EROCIPS project (Filipe and Pratas, 2007). A previous description of the risk model is available in ARCOPOL plus report (Fernandes, 2014).

The probability is based on dynamic marine weather conditions and statistical information (frequency constants for each accident type) from previous accidents. The severity of the consequences is the result of the combination of hypothetical spilled oil amount reaching shoreline and the coastal vulnerability on those affected areas.

In order to simplify the development of the scale of risk and its values, logarithmic values are used, defined by indexes, following IMO recommendations (IMO, 2002):

$$\log(Risk) = \log(Probability) \times \log(Severity) \tag{11}$$

Or

$$I_{RSI} = I_{PSI} + I_{SSI} \quad (12)$$

The full details about the risk assessment model implemented is described in section V.3.2.7)

V.3.2.3 Vessel information

Variable vessel information is used in the computation of risk. The properties used are the geographical position, cargo type, speed, vessel type, weight (DWT), name and ID (MMSI and IMO number). Vessels with less than 100 DWT, passenger vessels and fishing vessels navigating outside restricted waters are not considered in this study, based on the assumptions from Filipe and Pratas, 2007, and also for computational reasons (the risk model takes in consideration approximately 150 vessels every instant, after applying the mentioned filtering). It is assumed that a vessel is navigating in restricted waters if distance to shoreline is not greater than 3 nautical miles, or if water depth is not deeper than 20 meters.

The vessel information is obtained from AIS data. Presently the system is configured to seamlessly collect real time data from AISHUB.net or MarineTraffic API service, but the system can be easily adapted to collect information from any other online AIS data provider. The system is also prepared to import historical data.

V.3.2.4 Coastal vulnerability

The coastal vulnerability is used to quantify the consequences of shoreline contamination, on risk algorithm. This coastal vulnerability can be obtained from d-ifferent vulnerability indices: costal sensitivity index (*CSI*), socio-economic index (*SESI*) and ecological index (*ECSI*). Ecological index was not included yet in the pilot area, but the risk modelling system is prepared to include it, once data is available.

The characterization of the coastal sensitivity and socio-economic index in the pilot area (Portuguese continental coast) was made in the scope of EROCIPS project. Along with desk work, based on Aerial photos and on Google Earth, field surveys were conducted to the whole Portuguese continental shoreline. This information is available on the web through Google Earth (MARETEC, 2007), and this kml format is directly imported to the developed risk assessment tool.

The vulnerability indices obtained for the pilot area were defined with a very high spatial discretization, dividing the shoreline in multiple segments or stretches in extensions that can be as small as 200 meters, realistically representing the variability of the shoreline.

Coastal Sensitivity Index

This index (*CSI*) represents the quantification, in logarithmic scale, of the valuation of the environmental sensitivity (ecological, landscape) of the areas of the maritime coast and/or the surrounding waters that can be reached by sea pollution from hydrocarbons and/or other dangerous substances spills.

For the general group of areas of the maritime coast, NOAA's ESI (Environmental Sensitivity Index) was adapted for the Portuguese Continental Coast (modifications were related to the specificities of the Portuguese shoreline). The ranking of this index, which varies of 1 to 10, coincides with the scale of the NOAA's ESI (NOAA, 2002), defined to characterize zones of the shoreline in function of the following parameters:

- Exposure to wave and tidal energy
- Slope of the coast (intertidal zone)
- Type of substrate (size, permeability and mobility)
- Biological productivity and sensitivity
- Ease clean-up

The colours used to visualize the *CSI* ranking are the same as used in NOAA's ESI (a list description of *CSI* is included in Table 8).

Table 8 - Classes used for costal sensitivity index (*CSI*)

Colour	*CSI*	Colour code (RGB)			*CSI* and type of shoreline
		R	G	B	
	1	119	38	105	1A: exposed rocky shores 1B: Exposed, solid man-made structures
	2	174	153	191	Exposed Wave-cut Platform in Bedrock, Mud, or Clay. Medium slope
	3	0	151	212	Exposed fine to medium-grained sand dissipative beaches
	4	146	209	241	Exposed beaches with coarse grained or fine to medium-grained sand; sheltered beaches with fine grained sand
	5	152	206	201	Mixed sand and gravel beaches
	6	0	149	32	6A: Gravel beaches 6 B: Riprap
	7	214	186	0	Exposed tidal flats

	8	225	232	0	8A: Sheltered scarps in bedrock, mud or clay 8B: Sheltered, solid man-made structures
	9	248	163	0	9A: Sheltered tidal flats 9B: Sheltered low banks
	10	214	0	24	Salt and brackish waters marsh, freshwater marshes, swamps, mangroves or scrub wetlands

In regions like coastal shoreline (restricted) waters, commercial ports, and all-purpose terminals, fishing ports, marinas or yacht harbours, and unrestricted waters, *CSI* is invariable and considered to be 6. However, as this tool is only estimating risks of shoreline contamination, coastal vulnerability indices of restricted or unrestricted waters / open sea are not considered by the risk model.

The *CSI* values obtained in the pilot area vary from a range of 1 to 10, with an average value of 4.1 and a median value of 3.

Socio-economic Index

This index (*SESI*) intends to reflect the social-economic importance to the populations of the exploitation of the coastal zone under analysis (e.g. a beach not often used, or used but without significant infrastructures, and/or a beach with important economic value - restaurants, etc.). While the coastal sensitivity index *CSI* already considers the normal habitats for that shoreline, it does not consider other improvements that can exist in the zone and that are not specific of the characterization of index *CSI*, as fisheries or aquaculture, that have to be considered through the social-economic index *SESI*. This index varies from 1 to 5 (the complete list description of *SESI* is included in Table 9).

Table 9 - Classes used for socio-economical index (*SESI*)

SESI	Description
1	Area of none or very low importance in terms of environmental resources, leisure and other sea-related activities. Specific interests of the area are affected by the spill. Human population doesn't live directly or indirectly from the resources provided by sea-related activities.
2	Area of low importance in terms of environmental resources, leisure and other sea-related activities; Area of local interest. There is low investment that may be affected by the spill; Some interests of the area are affected by the spill.
3	Area of medium importance in terms of environmental resources, leisure and other sea-related activities; Area of medium regional and national interest. There is medium investment that may be affected by the spill. The spill affects the economy of the area and few economic aspects of neighbouring areas.
4	Area of high importance in terms of environmental resources, leisure and other sea-related activities; Area of high regional and national interest. Human population lives directly or indirectly from the resources provided by sea-related activities. The economy of the area and neighbouring areas can be affected by the spill; or there is high investment that may be affected by the spill.
5	Area of extreme importance in terms of environmental resources, leisure and other sea-related activities; Area of very high regional and national interest. There is very high investment and economy of the area that may be affected by the spill.

	Human population lives directly or indirectly from the resources provided by sea-related activities.

The *SESI* values obtained in the pilot area vary from a range of 1 to 5, with an average value of 1.8 and a median value of 1.

Ecological Index

The ecological index (*ECSI*) is used to consider special protected areas that are not included in the Coastal Sensitivity Index. This index varies from 1 to 5. Although the risk model is prepared to include this ecological index, this was not established yet for the area of study – therefore, a constant value of 3 is now temporarily used as *ECSI* in all shoreline stretches. Presently a methodological definition of this index is being pursued in the scope of ARCOPOL platform project.

V.3.2.5 Metocean data

Wind, currents, waves and visibility are taken into account for the probability of an accident, which is modified with correction factors adjusted by those meteo-oceanic conditions. These parameters can be imported to system's database in real-time from online internal or third party forecasting systems (as long as model output files are provided in native MOHID format - HDF5 - or in standard CF compliant netCDF formats, available online in web servers - preferably FTP or THREDDS catalogue) . The implemented system presented at this work imports MARETEC-IST's forecast regional solutions available online in http://forecast.maretec.org and http://meteo.ist.utl.pt.

Currents and water properties (temperature and salinity) are obtained from PCOMS-MOHID model (Mateus et al., 2012, Pinto et al., 2012). PCOMS is a 3-D hydro-biogeochemical model of the Iberian Western Atlantic region. Ocean boundary conditions are provided by the Mercator-Ocean PSY2V4 North Atlantic and by tidal levels computed by a 2-D version of MOHID (Neves, 2013; Ascione Kenov et al., 2014), forced by FES2004, and running on a wider region. PCOMS has a horizontal resolution of 6.6 km and a vertical discretization of 50 layers with increasing resolution from the sea bottom upward, reaching 1 m at the surface (Ascione Kenov et al., 2014).

Atmospheric conditions (wind velocity, surface air temperature, atmospheric pressure and visibility) are obtained from the meteorological forecasting system IST-MM5, using MM5 model (Grell et al.1994) with a 9km spatial resolution. This operational model was initially implemented by Sousa, 2002, and updated in 2005 (Trancoso, 2012). This model is also used as atmospheric forcing of PCOMS-MOHID.

The wave parameters (wave period, wave height, wave direction and wave length) are obtained from the Portuguese wave forecasting system implemented at MARETEC-IST, using WaveWatchIII model (version 3.14 – Tolman, 2009) with a 5km spatial resolution, and wind forcing provided by Global Forecasting System (GFS) from the National Oceanic and Atmospheric Administration (NOAA), with a spatial resolution of 0.5° (Franz et al., 2014).

These meteo-oceanic properties are also used to feed the oil spill fate and behaviour model integrated in the system, which is used to estimate the hypothetical vessel-based spilled oil amount reaching shoreline.

V.3.2.6 Oil spill model

The integrated oil spill model used in this work is MOHID oil spill fate and behaviour component, integrated in MOHID lagrangian transport module, where simulated pollutants are represented by a cloud of discrete particles (or super-particles) advected by wind, currents and waves, and spread due to random turbulent diffusion or mechanical spreading. MOHID oil spill modelling component was initially developed in MOHID in 2001 (Fernandes, 2001), and along all these years the model has been operationally applied in different incidents (Carracedo et al., 2006; Janeiro et al., 2014), field exercises and studies worldwide, allowing the simulation of all major oil transport and weathering processes at sea. The source code of oil spill modelling system was recently updated to include full 3D movement of oil particles, wave-induced currents, and oil-shoreline interaction (Fernandes et al., 2013), as well as blowout emissions (Leitão, 2013).

This oil spill model has the ability to run integrated with hydrodynamic solution, or independently (coupled offline to metocean models), being this last one the adopted option for integration in the developed dynamic risk tool, taking advantage of metocean models previously run, and thus optimizing the computational efficiency.

The oil spill model is freely available for public access, since it is integrated in MOHID numerical modelling system which follows a FOSS (free / open source software) strategy.

The dynamic risk tool continuously runs MOHID oil spill model to simulate hypothetical spills from multiple vessels across the coast, and then taking into account the fraction of oil that would approach the coastline.

V.3.2.7 Risk model

Two different integrated risk types (they are integrated because they take into consideration different types of incidents) are computed: a) risk of oil spill incident; b) risk of shoreline contamination.

Both integrated risk types are variable in space and time due to variable vessel information and metocean conditions (that influence probability of an accident, as well as fate and behaviour of oil spills simulated). The simultaneous calculation of the risk posed by each vessel crossing a pilot area is integrated, allowing the generation of a dynamic shoreline risk map for that zone.

Risk of oil spill incident

The risk of oil spill incident quantifies the severity based on vessel dead weight tonnage and vessel position, with higher or lower risk, if the vessel is navigating in restricted or unrestricted waters, respectively. This risk type does not take into consideration the effects on shoreline, and is represented in each vessel.

Different types of incidents are considered in the risk model: grounding, foundering and structural failures, collision (with a ship or with port facilities), fire and explosion, illegal and operational discharges. In order to obtain the integrated ship risk of spill incident, the partial probability and severity indices are integrated. Probability indices from the different types of incidents are summed up, and a weighted average severity index from the different types of incidents is determined. The sum of the probability indices ($I_{\Sigma PSI}$) with the weighted average severity index ($\overline{I_{SSI}}$) provides the integrated risk of spill incidents (I_{IRSI})

$$I_{IRSI} = I_{\Sigma PSI} + \overline{I_{SSI}} \tag{13}$$

The full detailed formulation on determination of $\overline{I_{SSI}}$ and $I_{\Sigma PSI}$ is explained in Annex 2.

Risk of shoreline contamination

The risk of shoreline contamination takes into account the interaction with the coastline, therefore the severity / shoreline consequences additionally include the virtual spilled oil fraction reaching shoreline and its environmental and socio-economic vulnerabilities, instead of simply considering the vessel deadweight tonnage and position. The oil reaching shoreline is quantified with an oil spill fate and behaviour model that continuously simulates virtual oil spills from the vessels included in the domain. Alternatively, a “non-modelled” shoreline contamination risk rating is computed, without using oil spill model for the determination of shoreline impact - in this case, a vessel shoreline proximity correction factor is used and subtracted to the risk value (with this correction factor decreasing as the vessel approaches the coastline). This risk type is represented in shoreline stretches, taking into consideration the effects from multiple vessels affecting that zone. The division of shoreline stretches for characterization of shoreline contamination risk is based on the same division used in the coastal vulnerability characterization.

The shoreline contamination risks provided are in fact a percentile (by default, percentile 98, but can be customized) of the shoreline contamination risks determined from the different vessels. Shoreline contamination risks below a user-defined value are not considered.

Probability

The probability / frequency of occurrence of a specific type of incident in a ship leading to an oil spill, is obtained from statistical constants (frequency of incidents per distance navigated, or annual incident frequency) corrected with a combination of a different factors identified as relevant in the generation of those incidents (e.g. visibility, currents, proximity to coast, etc.).

The choice of using probability of incidents for each vessel per distance unit navigated lay in the fact that the annual frequency of accidents is too static, i.e. if hypothetically there is a ship anchored off an entire year, it will still provide a risk similar to a ship in circulation, which is not entirely true. A dynamic probability will be inevitably achieved using frequency of accidents per km navigated times the distance navigated in a given period of time.

Generically, the probability of incident in a specific time period is computed like this:

$$P = C \times \Delta S \times I \tag{14}$$

where C is the frequency constant (accidents.km^{-1}), ΔS is the distance navigated by the ship (in km), and I is the multiplying correction factors.

The distance navigated by the ship is obtained directly by ship velocity (from AIS data) and time step for risk analysis (defined by the end-user).

Since illegal / operational discharges occur based on human decisions, their probability is not influenced by environmental conditions. Thus, no correction factors are applied to the calculation of this probability. Also in this type of incident, the probability is not based on incident frequency per distance navigated, but in annual frequency – it is assumed that deliberate discharges occur independently of vessel speed. The probability of operational discharges (P_{OD}), is determined as follows:

$$P_{OD} = \frac{C_{annual}}{365} \times \Delta t \tag{15}$$

where C_{annual} is the frequency constant (incidents per year) and Δt is the time step used in the risk tool (in days).

A logarithmic scale from 1 to 8 was adopted for the index of probability. The correspondence between annual probability and index of probability can be represented by the following equation (7) (derived from the Table 10), based in Filipe and Pratas, 2007, and inspired by IMO recommendation (IMO, 2002):

$$I_{PSI} = \log(P_{annual}) + 6 \quad (I_{Pmin} = 0;\ I_{Pmax} = 8) \tag{16}$$

The annual probability (P_{annual}) is based on the next equation:

$$P_{annual} = 365 \times \frac{P}{\Delta t} \tag{17}$$

P is the probability obtained by the previous method explained in this chapter, for a specific time step Δt (in days).

Table 10 - Classification of probability of ship incidents and correspondence between annual probability and index of probability (obtained from Filipe and Pratas, 2007, and inspired by IMO recommendation - IMO, 2002).

Probability / Frequency	Definition	Annual Probability / Frequency (P_{annual})	Index of Probability (I_{PSI})

Very High	Likely to occur once or more per month	10 to 100 or more	> 7 - 8
High	Likely to occur once to 10 times per year	1 to 10	> 6 – 7
Medium	Likely to occur once in a period from 1 to 10 years	10^{-2} to 1	> 4 – 6
Low	Likely to occur from 0.5% to 50% within a period of 50 years	10^{-4} to 10^{-2}	> 2 – 4
Very low	Likely to occur from 0.05% to 0.5% within a period of 50 years	10^{-5} to 10^{-4}	0 - 2

To estimate the index of probability, frequency constants obtained from reported spill incidents are used (per distance unit navigated or annual frequency for illegal / operational discharges) for the various types of accidents.

- **Frequency constants**

Different frequency / probability constants of incidents are included in the risk model as a way to include some differentiation based on type of incidents and some probabilistic data obtained from statistical information on past incidents. These values can be changed by the end-user in any moment.

In this study, frequency constants of incidents per distance unit navigated are obtained from IAEA, 2001, and missing constants are obtained from the combination of previous report with Lloyd's Register accidents database (relation between annual frequency constants was used to extrapolate frequency constants per distance navigated). The numerical values of the frequency constants used can be found in Annex 2, Table 34.

According to IAEA, 2001, the frequency of incidents due to fire & explosion does not vary significantly with the region. Therefore, the frequency for this type of accidents per distance navigated is kept constant.

Also in the same report, there is no reference to illegal / operational discharges. For this kind of incident, annual incident frequency is assumed, since these discharges are independent of vessel speed. It is also assumed that such discharges do not occur in restricted waters.

- **Multiplying correction factors**

Multiplying correction factors are used to modify the probabilities of spill incidents based on metocean conditions (wind velocity, currents velocity, wave height, and visibility), proximity to coast and ship type. The correction factors are not applied to the probability of having operational / illegal discharges because these incidents are considered deliberate or independent from and not controlled by external effects. The values used can also be changed or calibrated by the end-user.

The correction factors included by default in this study were obtained from Risk Assessment Report for the Portuguese and Galician Coast – EROCIPS (Filipe and Pratas, 2007), and the values used are listed in detail in Table 11. The Table 12 summarizes the multiple correction factors used by each type of accident.

Table 11 - Correction factors related related to currents (I_{curr}), wind velocity (I_{wind}), proximity to shoreline (I_{prox}), visibility (I_{visib}), significant wave height (I_{wav}) and ship type (I_{ship})

Property / Correction Factor	Category		Type of incident: Ship to ship collision	Collision with port facilities	Foundering	Grounding	Grounding during navigation	Drift Grounding	Fire / explosion
Currents velocity (m s^{-1}) I_{curr}	≥ 1.54 (3 knots)		2.0						
	≥ 1.03 (2 knots) and < 1.54 (3 knots)		1.6						
	≥ 0.51 (1 knot) and < 1.03 (2 knots)		1.2						
	≥ 0.36 (0.7 knots) and < 0.51 (1 knot)		0.8						
	< 0.36 (0.7 knots)		0.4						
Wind velocity (m s^{-1}) I_{wind}	≥ 25 (90 km h^{-1})		2.0						
	≥ 13.89 (50 km h^{-1}) and < 25 (90 km h^{-1})		1.6						
	≥8.33 (30km h^{-1}) and <13.89 (50 km h^{-1})		1.2						
	< 8.33 (30 km h^{-1})		0.8						
Proximity to shoreline (m) I_{prox}	<= 11120 (6 nautical miles)		2.0						
	> 11120 (6 nautical miles) and ≤ 14816 (8 nautical miles)		1.0						
	> 14816 (8 nautical miles)		0.8						
Visibility (km) I_{visib}	≥ 1.85 (1 n.m)		0.24	-	0.6	-	-	-	-
	< 1.85 (1 n.m.)		1.76	-	1.4	-	-	-	-
Wave height (m) I_{wav}	≥ 2.5m				1	-	1.4	1.78	-
	< 2.5m				0.1	-	0.6	0.22	-
Type of incident I_{ship}	Restricted waters	Tankers	1.7	1	-	1.6	-	-	0.573
		Cargo	2.0	1	-	1.6	-	-	2.656
		Fishing	0.3	0.7	-	0.2	-	-	0.3
	Unrestricted waters	Tankers	1.629	-	0.113	-	0.612	1.6	1.629
		Cargo	3.343	-	3.606	-	4.286	2.133	3.343

Table 12 - Summary of multiple correction factors used by each type of accident (I_{curr}: correction factor due to currents; I_{wind}: correction factor due to wind; I_{prox}: correction factor due to proximity to coast; I_{ship}: correction factor due to ship type; I_{visib}: correction factor due to visibility; I_{wave}: correction factor due to waves)

<table>
<tr><th colspan="2">Restricted Waters</th><th colspan="2">Unrestricted Waters</th></tr>
<tr><th>Type of Accident</th><th>Correction Factors (I)</th><th>Type of Accident</th><th>Correction Factors (I)</th></tr>
<tr><td>Ship to Ship Collision</td><td rowspan="4">I_{curr} x I_{wind} x I_{ship}</td><td>Ship to Ship Collision</td><td>I_{curr} x I_{wind} x I_{visib} x I_{wave}</td></tr>
<tr><td>Collision with Port Facilities</td><td>Foundering</td><td>I_{wave}</td></tr>
<tr><td rowspan="2">Grounding</td><td>Grounding During Navigation</td><td>I_{curr} x I_{wind} x I_{visib} x I_{wave} x I_{prox}</td></tr>
<tr><td>Drift Grounding</td><td>I_{curr} x I_{wind} x I_{wave} x I_{prox}</td></tr>
<tr><td>Fire / explosion</td><td>I_{ship}</td><td>Fire / explosion</td><td>I_{ship}</td></tr>
</table>

- **Minimum risk / minimum probability**

A minimum or residual probability of an accident per unit time must be assumed, to avoid the determination of null or (nearly null) probabilities when vessels are anchored or moving very slowly (because the risk model computes the incident probability based on ship velocity). Even at slow motion or stopped, a ship has always a risk of a spill accident. For instance, there is still a chance of collision with another ship, or to anchor in a danger zone and eventually generate a grounding accident (depending on the weather and oceanographic conditions).

This probability is obtained in function of a minimum velocity. Below this velocity value, the vessel is assumed to have a constant accident probability. The minimum velocity is user-defined, and by default the value of 0.36 m/s was adopted (selection based on the minimum value corresponding to the lower correction factor for currents velocity).

Severity

The severity index list of hydrocarbon and other hazardous substances spills, whether in open sea or in restricted waters due to the various types of accidents, follows IMO recommendations (IMO, 2002) and is described in Filipe and Pratas, 2007. A logarithmic scale from 1 to 8 was adopted, following the same scale as probability index (Table 13).

Table 13 - Classification of severity of ship incidents and correspondence between severity and index of severity

Severity degree	Impacts			Severity Index (I_{SSI})
	Human health	Environment	Socio-economical activities	
Catastrophic	Catastrophic number of injuries, fatalities and physical disabilities	Catastrophic and permanent damage to the marine flora and fauna.	Affecting in a catastrophic scale and for long periods of time	> 7 - 8
Extreme	Extremely number of injuries, fatalities and physical disabilities	Extreme and permanent damage to the marine flora and fauna	Affecting at extreme scale and for long periods of time	> 6 – 7
Very high or very serious	Very high number of injuries, fatalities and physical disabilities	Very serious and almost permanent damage to the marine flora and fauna.	Affecting at very high scale and for long periods of time	> 5 – 6
High or serious	High number of injuries, or physical disabilities	Long term damage to the marine flora and fauna. High cost of measures needed to restore the resources affected by the spill	Affecting at high scale and for long periods of time	> 4 – 5
Medium or moderate	Medium number of injuries (unlikely to result in physical disabilities)	Medium term damage to the marine flora and fauna. Moderate cost of measures needed to restore the resources affected by the spill	Affecting at medium scale and for long periods of time	> 3 – 4
Little or slight	Little number of injuries	Short term damage to the marine flora and fauna. Low cost of measures needed to restore the resources affected by the spill.	Affecting at little scale and for long periods of time	> 2 – 3
Very little or very slight	Very little number of injuries. Very little first aid assistance	Very short-term damage to the marine flora and fauna. Very low cost of measures needed to restore the resources affected by the spill.	Affecting at little scale and for long periods of time	> 1 – 2
Insignificant	No reported harm to human health	No damage to the marine flora and fauna. No restoration measures needed	No effects	> 0 – 1

- **Severity of risk of spill incident**

The severity in the risk of spill incident varies with the ship position (restricted / unrestricted waters), and with the hypothetical amount of spilt product (Q). Typical values of amount of oil spilt are estimated based on the ship type, weight (DWT) and the type of incident, in order to estimate the severity index of spill incident (I_{SSI})

according to the values in Filipe and Pratas, 2007. Further detailed information on the formulations used are listed in Table 14 and Table 15.

Table 14 - Average amount of spilled oil per incident type and ship type.

Type of incident	Equation Q = oil amount (ton); DW = Deadweight (DWT)		
	Tanker (crude)	Fishing Vessels (diesel)	Cargo (bunker)
Ship to ship collision	$Q = 1E\text{-}07DW^2 + 0.0327DW$	$Q = 6$	$Q = 60$
Collision with port facilities	$Q = 5E\text{-}08DW^2 + 0.0134DW$	$Q = 3$	$Q = 25$
Foundering	$Q = DW$	$Q = 12$	$Q = 1300$
Grounding	$Q = 5E\text{-}07DW^2 + 0.1362DW$	$Q = 2$	$Q = 130$
Fire & Explosion	$Q = 0.8DW$	$Q = 10$	$Q = 100$
Illegal / operational discharges	$Q = 25$[2]	$Q = 3$[2]	$Q = 7$[2]

Table 15 - Quantification of severity index of spill incident, based on oil amount ship type.

Ship type	Unrestricted waters	Restricted waters
Crude (tanker)	$I_{SSI\_unsrestricted} = 0.4037\ln(Q) + 1.9534$ $I_{SSI\_unrestricted\_min} = 0$; $I_{SSI\_unrestricted\_max} = 8$	$I_{SSI\_restricted} = 0.4693\ln(Q) + 1.9903$ $I_{SSI\_restricted\_min} = 0$; $I_{SSI\_restricted\_max} = 8$
Diesel (fishing)	$I_{SSI\_unrestricted} = 0.4343\ln(Q) + 1.301$ $I_{SSI\_unrestricted\_min} = 0$; $I_{SSI\_unrestricted\_max} = 7$	$I_{SSI\_restricted} = 0.4689\ln(Q) + 1.666$ $I_{SSI\_restricted\_min} = 0$; $I_{SSI\_restricted\_max} = 8$
Bunker (cargo)	$I_{SSI} = 0.3996\ln(Q) + 1.9285$ $I_{SSI\_unrestricted\_min} = 0$; $I_{SSI\_unrestricted\_max} = 8$	$I_{SSI\_restricted} = 0.4517\ln(Q) + 2.1643$ $I_{SSI\_restricted\_min} = 0$; $I_{SSI\_restricted\_max} = 8$

- **Severity of risk of shoreline contamination**

As mentioned before, the risk of shoreline contamination from each vessel considers the risk of spill incidents plus the interaction with the coast, taking into consideration the coastal vulnerability, and the potential contamination in the near-shore. This potential contamination is computed by two different approaches: by estimating the oil fraction reaching the coastline – method herein called as "modelled" risk of shoreline

[2] Values used are the worst-case values / highest values for the different types of operational / illegal discharges

contamination; or alternatively by a correction factor based on ship distance to coastline – method herein called as "non-modelled" risk of shoreline contamination.

In both approaches (modelled and non-modelled), the computed severity index of shoreline contamination (I_{SSC}) includes the severity index of risk of spill incident (I_{SSI}) mentioned in the previous section, with a weight of 50%. The remaining 50% of severity are obtained from the coastal vulnerability index (I_V), as expressed by the next formula:

$$I_{SSC} = 0.5 \cdot I_{SSI} + 0.5 \cdot I_V \tag{18}$$

Where coastal vulnerability index can be represented as an arithmetic mean from the different coastal vulnerability indices:

$$I_V = \frac{8}{5} \cdot \left(\frac{0.5CSI + SESI + ECSI}{3} \right) \tag{19}$$

The fraction 8/5 is used to convert the vulnerability index scale (from 1-5 to 1-8), to the same scale adopted in severity of spill incident, as well as in probability index. *CSI* is multiplied by 0.5 to convert the scale from 1-10 to 1-5 (as adopted in *SESI* and *ECSI*).

For non-modelled risk, a vessel shoreline proximity correction factor is subtracted to the severity of spill incident index (with this correction factor decreasing as the vessel approaches the coastline), as can be shown in the next equation:

$$I_{SSC(non-modelled)} = I_{SSC} - F_{SS} \text{ with } F_{SS} \leq I_{SSC} \tag{20}$$

The determination of this factor (F_{SS}) depends on distance between spill site and shoreline (D_{SS}), and on type of oil product / ship type (Table 16). The values used here are based on Filipe and Pratas, 2007. Since in that report, the correction factor was applied in a scale between 1 and 15, and in this work the correction factor is applied in severity index, between 1 and 8, a multiplying factor of $\frac{8}{15}$ is applied to transform the correction factor to the appropriate scale.

Table 16 - Subtracting correction factor (F_{SS}) based on spill site used, in function of ship type and distance between spill site and shoreline (D_{SS})

Ship Type	Equation for Correction Factor (F_{SS})
Fishing (Diesel)	$F_{SS} = \frac{8}{15} \cdot 0.3 \cdot D_{SS}$
Tanker (Crude)	$F_{SS} = \frac{8}{15} \cdot 0.2 \cdot D_{SS}$
Cargo (Bunker)	$F_{SS} = \frac{8}{15} \cdot 0.1 \cdot D_{SS}$

For modelled risk, a modified severity of spill incident is adopted, in a more complex and realistic approach to determine the impact risk of oil spills on the shoreline, since fate and behaviour of oil spilled is taken into account, using MOHID oil spill model, as described in section 2.6. The modified severity of spill incident is obtained by using the regular equation for severity of spill incident in restricted waters (Table 15), but with a modified amount of oil spill (Q*) used instead of Q, which is computed as follows:

$$Q^* = \frac{Q \times M}{L_{stretch}} \times L_{unit} \quad (21)$$

M is the modelled ratio of oil reaching near the shoreline stretch in a user-specified time period, $L_{stretch}$ is the shoreline stretch extension (m), and L_{unit} is the shoreline stretch extension unit used (by default is 1000m, but end-user can change this value). Q is the amount of oil based on ship type, weight and the type of incident. Thus, Q* is the maximum amount of oil spilled reaching near the shoreline stretch per shoreline extension unit, in a certain time period. An increase in L_{unit} will generate higher severity indexes, so this value needs to be properly calibrated.

The quantification of modelled maximum oil contaminating a specific shoreline stretch is based on the maximum amount of oil present inside an area near the referred shoreline stretch. The definition of this "near-shore" area for each shoreline stretch is based on the distance to the shoreline stretch; thus, if the modelled oil reaches this near-shore area, is assumed as relevant to the quantification of shoreline contamination risk. The near-shore distance is user-defined, and by default it is assumed a value of 2000m from the coast. The time period used in the quantification of maximum oil spilled reaching near the shoreline stretch has a default value of 24 hours (configurable). Updates and new oil spill simulations from updated vessel positions are made every hour (this value is also configurable). The oil spill model simulations are made assuming always the same oil product released. The oil product included in the risk model (Carpinteria, medium oil from Group III) was chosen based on the profile of being a “worst case scenario” for shoreline contamination, being a crude product from oil group III with low weathering effects along time.

Risk matrix

The risk matrix is the result of crossing both probability and severity indices, in order to obtain a risk rating – Table 17. The sum of both indices generates a risk index classification scale between 2 and 16. These values are categorized with different risk levels and corresponding colours.

Independently of the integrated risk types applied (e.g. risk of spill incident; modelled risk of shoreline contamination; non-modelled risk of shoreline contamination), the same risk matrix should be applied.

In the case of shoreline contamination risk, at the present stage of the work, the visualization of risk values in the implemented software tool follows a continuous risk scale (bounded by the same limits as defined in the risk matrix categorization scheme), instead a categorized scale, and using a different colour pattern from the proposed in Table 17. This option facilitates the visualization of variability in shoreline risk levels during the development period. In the future, the visualization of this risk level will be updated to the categorized view and using the same colour pattern defined and presented in Table 17.

No risk acceptance / tolerability criteria were defined in the present work.

Table 17 - Risk matrix based on probability and severity indices, with corresponding representation with colour. $2<I_{RSI}\leq5$ (normal text): dark green - very low or insignificant risk; $6\leq I_{RSI}\leq7$ (italic text): light green – low or minor risk; $8\leq I_{RSI}\leq9$ (bold text): yellow – medium or moderate; $10\leq I_{RSI}\leq11$ (underline text): orange – high level or serious; $12\leq I_{RSI}<16$ (underline + bold text): red – very high or critical).

Risk Index (I_{RSI})		Severity Index (I_{SSI})							
		1	2	3	4	5	6	7	8
Probability (I_{PSI})	1	2	3	4	5	*6*	*7*	**8**	**9**
	2	3	4	5	*6*	*7*	**8**	**9**	10
	3	4	5	*6*	*7*	**8**	**9**	10	11
	4	5	*6*	*7*	**8**	**9**	10	11	**12**
	5	*6*	*7*	**8**	**9**	10	11	**12**	**13**
	6	*7*	**8**	**9**	10	11	**12**	**13**	**14**
	7	**8**	**9**	10	11	**12**	**13**	**14**	**15**
	8	**9**	10	11	**12**	**13**	**14**	**15**	**16**

V.3.2.8 Development of software

This risk assessment methodology has been implemented as a plugin from MOHID Studio, which is a GIS desktop interface that can also be used to run MOHID water modelling system. MOHID Studio is a commercial platform property of Action Modulers, and has been entirely developed in c#.NET language, using SQL Server components and MOHID model.

The main philosophy of the software architecture was to create separate layers, allowing distributed tasks in different processes or computers, and a lighter graphic user interface (GUI). The general information workflow in the software framework is presented in Figure 50. According to this, the main software framework is composed by four main components, exchanging information between them:

- an SQL Server or SQL Lite database, where all the data and meta-data is stored (metocean model outputs are not stored; only indexed);
- a desktop service (Action Server), which is continuously loading / downloading updated data from different data sources (AIS data, metocean model outputs, etc.), managing MOHID oil spill model, processing all information (and computing risk levels) and storing data on database;
- MOHID oil spill project / executable file, which is continuously generating and running virtual oil spill simulations based on ship positions, and on instructions managed by Action Server desktop service.
- A Graphic User Interface (MOHID Studio), directly connected to the database, and showing requested data to the end-user. MOHID Studio can also be used to configure Action Server, and to run on-demand risk assessment tool for specific periods.

MOHID Studio and Action Server don't need to be running on the same computer. The software architecture has also been developed to enable the publication of real-time risk mapping data in external platforms, including WMS layers, to facilitate the interoperability of the system.

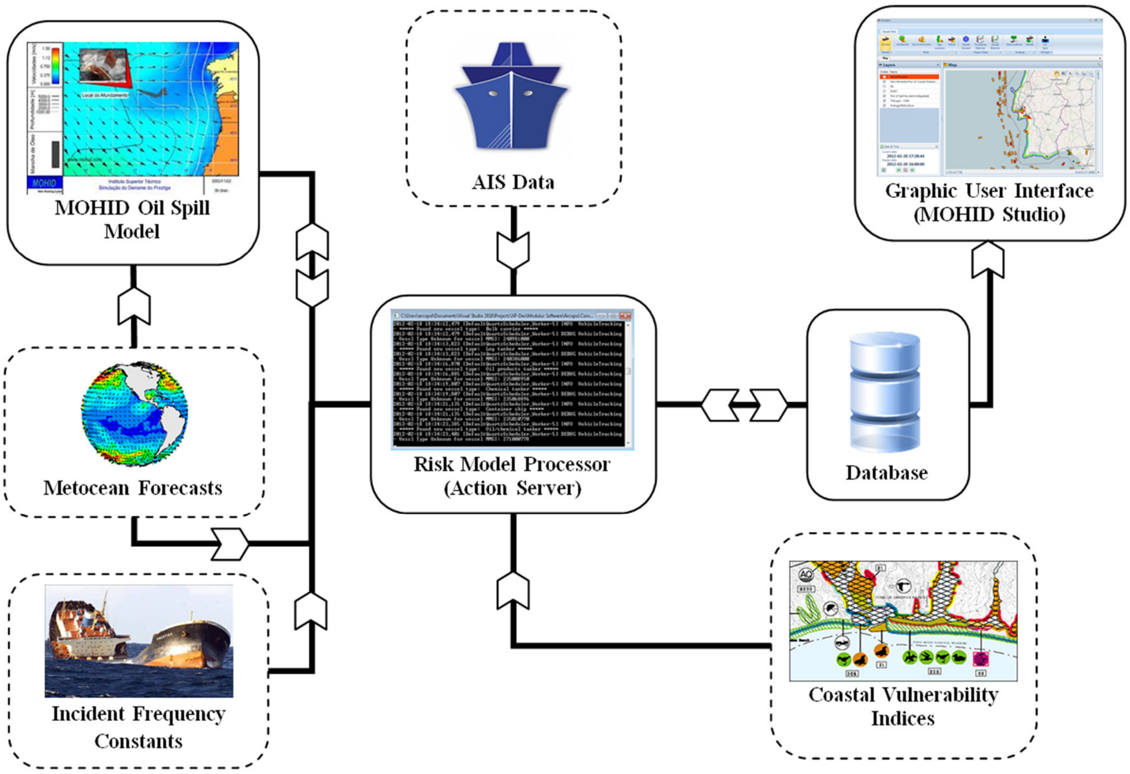


Figure 50 - General information workflow in the risk modelling system

V.3.3 Results

In this section, the response of the proposed risk model to different metocean conditions is evaluated in the pilot area, and the graphic user interface developed in this work is also presented. Since the dynamic risk tool is capable of running in real time or on-demand (for historic periods or virtual scenarios), it is assumed that a dynamic behaviour and proper response to the different variables means that the developed tool is also ready and able to provide results in an operational way.

V.3.3.1 Graphic User Interface

The risk modelling tool is able to run in continuous mode, allowing the user to follow in real-time the ship traffic and specific vessel details, the evolution of risks crossed with background dynamic web maps (e.g. Google maps, Bing Maps, Open Street Maps) and many other geographic layers and features (Figure 51) – e.g. visualizing metocean fields, topography, running oil spills on-demand, etc.

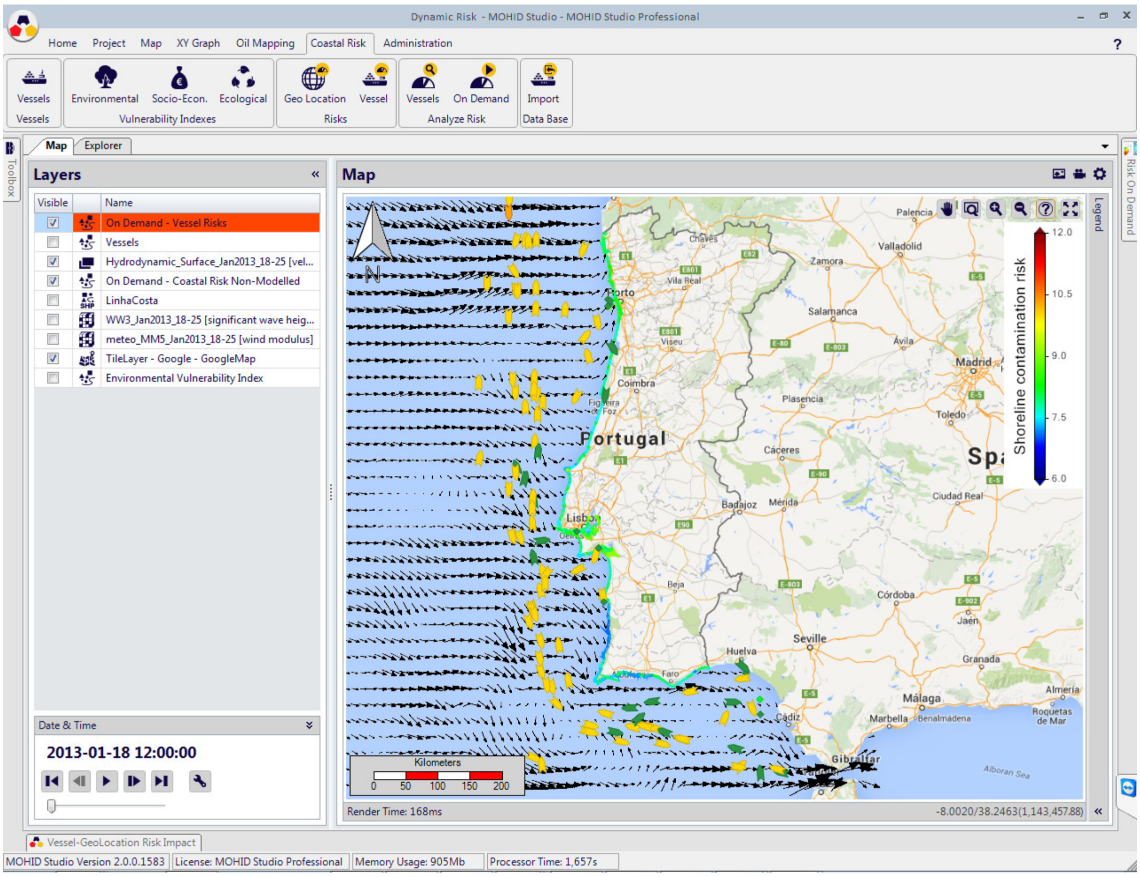


Figure 51 - Graphic User Interface layout, with simultaneous visualization of ship incident risks, shoreline contamination risks, surface water velocity and Google map layer. Ship incident risk colours presented in categorized view (green, yellow, orange and red colours).

When zooming the view, it is possible to check the very high level of resolution of the vulnerability indices and the associated risk levels being computed (Figure 52).

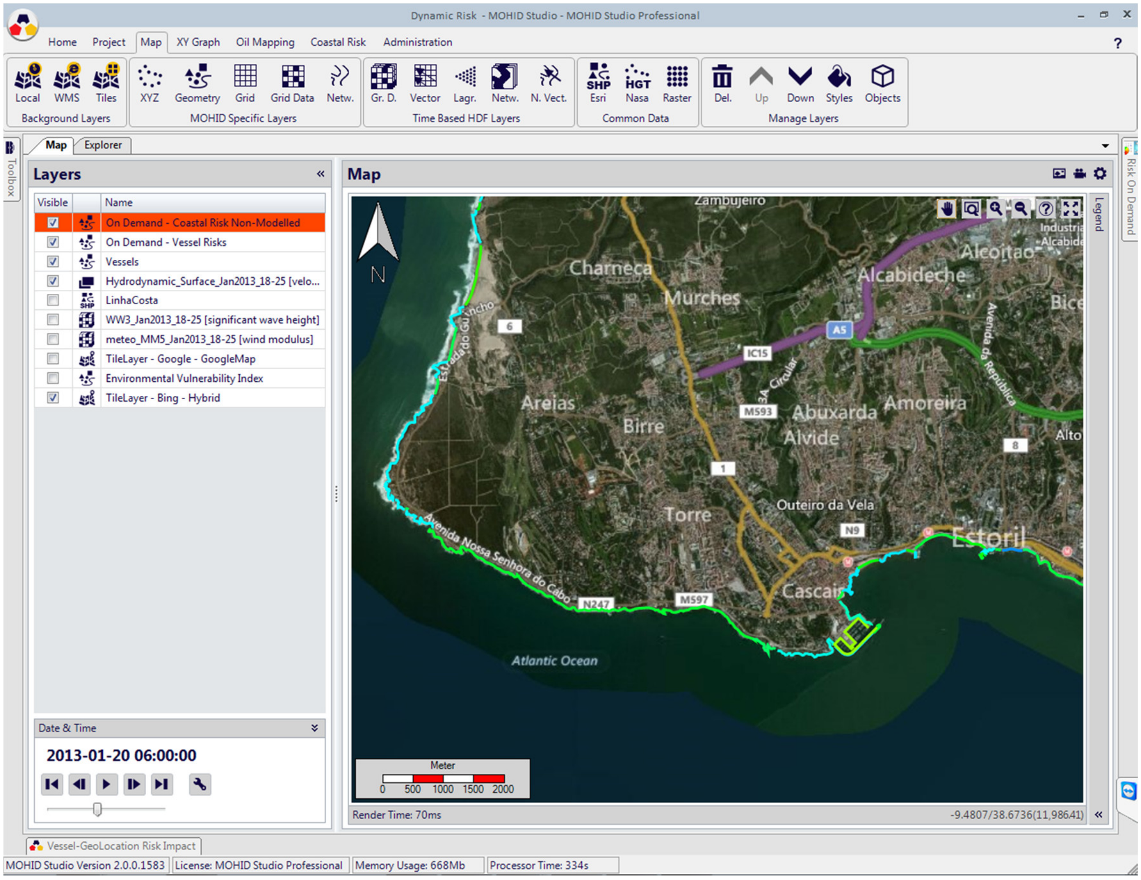
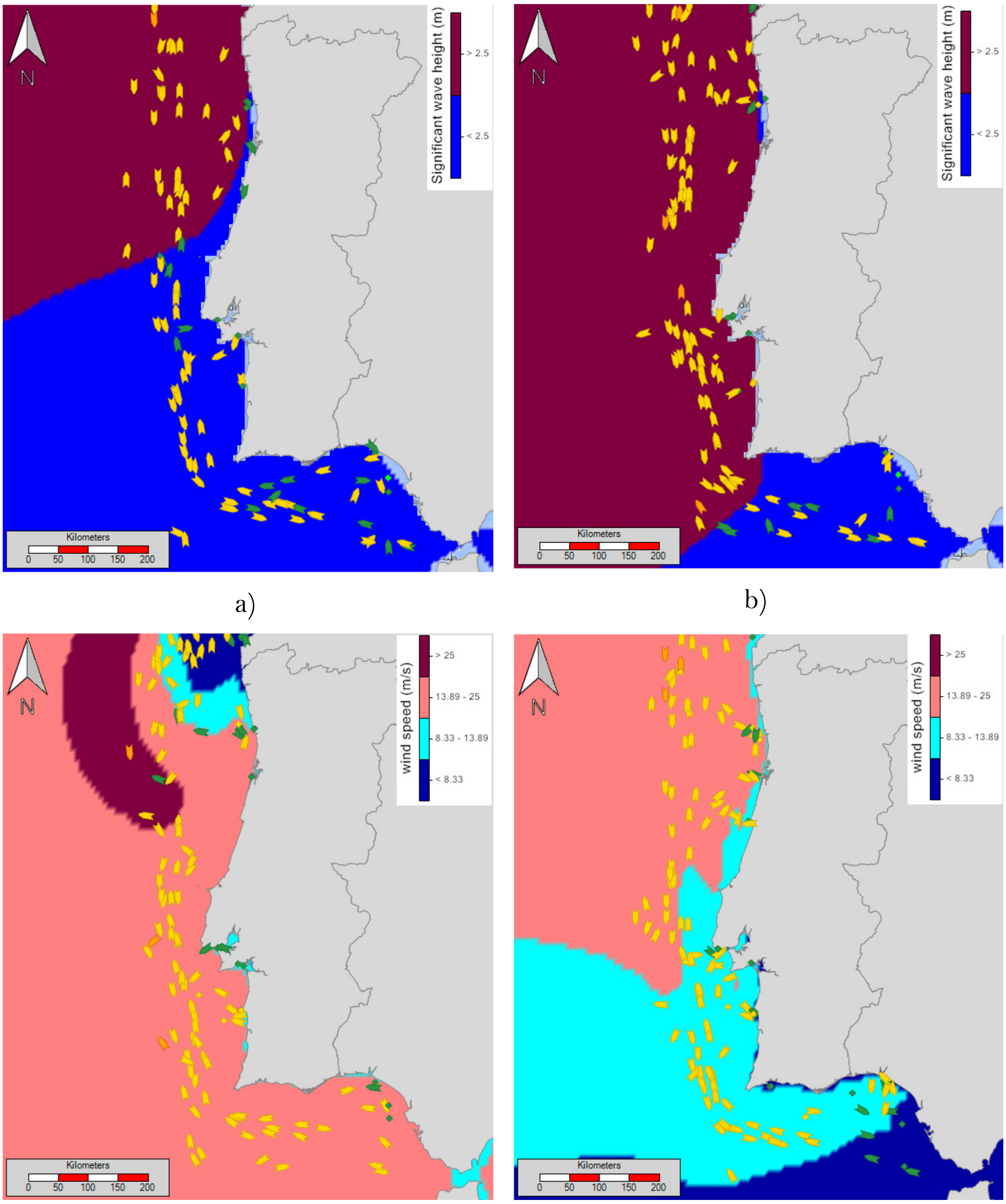


Figure 52 - Zoomed image of the Graphic User Interface for the Lisbon area – simultaneous visualization of coastal sensitivity index and Bing Hybrid map layer.

V.3.3.2 Ship incident risk

Metocean conditions have direct effect on risk of ship incident, because they can influence the probability of an accident occur, according to the methodology proposed. These effects are included in the risk model through categorized correcting factors based on the range of metocean conditions.

One of the exercises performed in this study was to analyse the evolution of ship incident risks according to some of these metocean conditions used, organized in the same classes as the ones used in the correcting factors. In Figure 53, ship incident risk levels are shown in different colour classes for different instants, together with wave model data (Figure 53a and Figure 53b) and wind speed (Figure 53c and Figure 53d) used in the risk model. Generally, the lower ship incident risk levels (in green) are present in ships crossing geographical areas where wind or wave conditions belong to lower classes. The same behaviour can be seen with vessels with higher incident risk levels – they tend to be determined in vessels crossing areas where wind speed or significant wave height are greater. It is also clear in Figure 53 that the presence of a ship in different wave classes can contribute more significantly for different risk levels than wind speed – this is due to the fact that the wind multiplying correcting factor varies from 0.8 to 2, while the wave correcting factor used varies from 0.1 to 1 or 0.22 to 1.78 (detailed values on correcting factors in Table 11).



a) b)

c) d)

Figure 53 - Ship incident risk levels (green ships mean lower risk, yellow means medium risk and orange ships mean higher risk) in the pilot area with background metocean conditions used. a) and b): Significant wave height in 18-1-2013 12:00 and 19-1-2013 00:00 respectively; c) and d): Wind speed in 19-1-2013 06:00 and 22-1-2013 06:00, respectively.

A better evaluation of the importance of metocean conditions in the risk model can be tested using different metocean conditions for the same ship positions. Figure 54 illustrates the ship incident risk levels using different metocean conditions (6 months later), and exactly the same ship information as used in Figure 53. Figure 54 clearly shows the dynamic change of risk levels directly affected by the wind and waves, for the same vessel traffic. Comparing Figure 54 with Figure 53, different ship risk levels can be observed. The effects of the other environmental conditions (visibility and surface water velocity) are similar to the properties illustrated here.

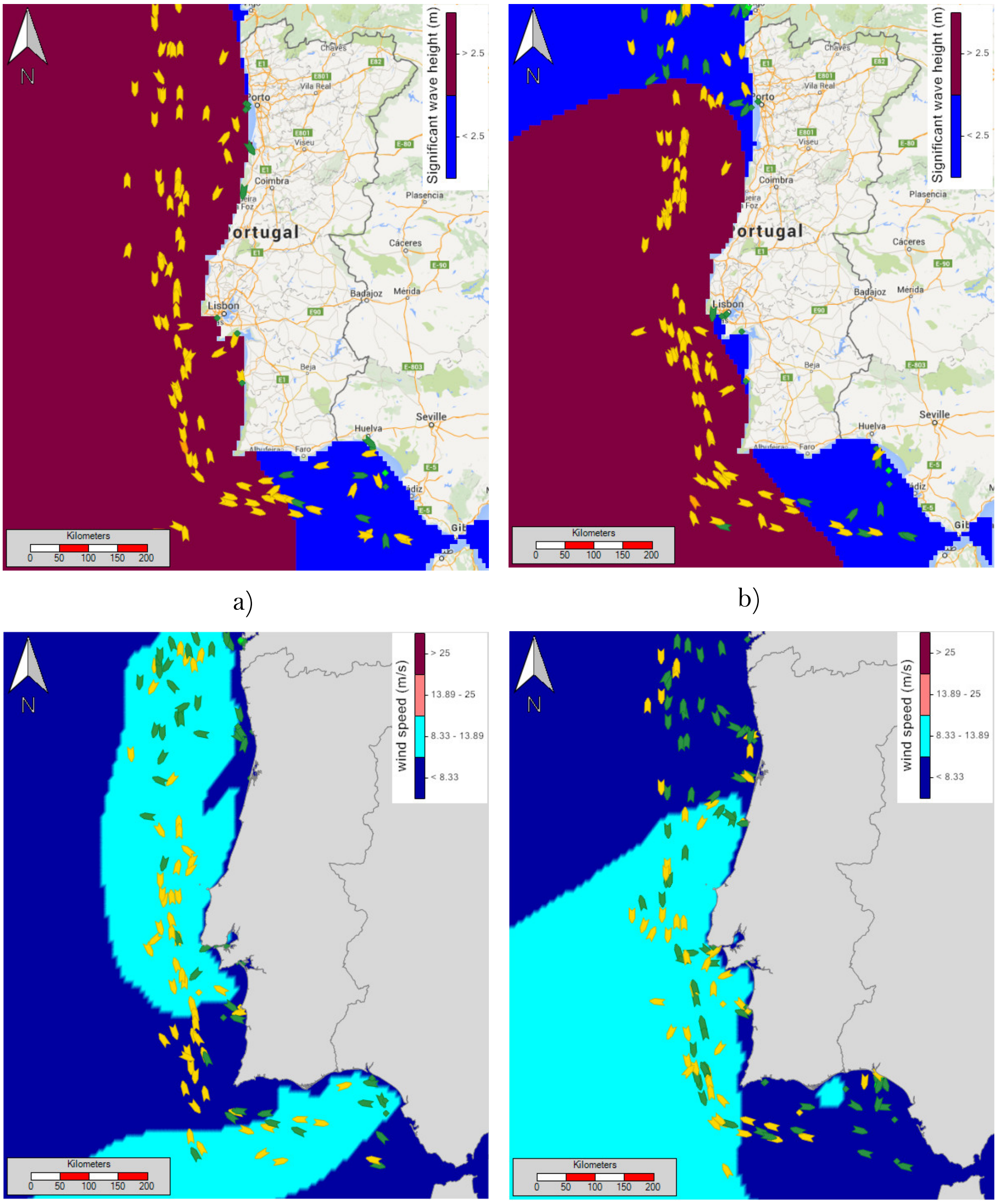


Figure 54 - Ship incident risk levels (green ships mean lower risk, yellow means medium risk and orange ships mean higher risk) in the pilot area with background metocean conditions used. Computation is made with same vessel positions as used in Figure 53 a) and b): Significant wave height in 18-6-2013 12:00 and 19-6-2013 00:00 respectively; c) and d): Wind speed in 19-6-2013 06:00 and 22-6-2013 06:00, respectively.

V.3.3.3 Shoreline contamination risk

When compared with ship incident spills, the evaluation of shoreline contamination risk from spills is more complex, as this parameter depends additionally on the coastal vulnerability indices, and is a result of an integration of risks from the different ships affecting each shoreline stretch. While it is easy to find different shoreline risk levels along the coast (e.g. Figure 51), it can be difficult to evaluate, isolate and study the dependence of risk model on the multiple factors – for instance, metocean conditions, vessel traffic conditions, coastal vulnerability, oil transport and weathering module. To facilitate the analysis, at this chapter we will start by evaluating the risk model behaviour without integrating the oil transport and weathering module (this matter is studied in subchapter V.3.3.4).

Evaluating dynamic response to vessels in the proximity

In order to achieve this objective, an initial study was performed, with the selection of two different locations with exactly the same coastal vulnerability (Figure 55), and subject to the same metocean conditions along the simulation. Therefore, the shoreline contamination risk levels are only influenced by the different vessels in the proximity. The results were generated, based on the registered vessel positions from two one-week periods (between 18-1-2013 to 25-1-2013 and between 18-6-2013 to 25-6-2013), generating model risk outputs every 6 hours. The metocean conditions were defined as constant in the whole model domain along the two simulation periods. Typical winter (rough) and summer (calm) conditions were defined for January and June periods, respectively. Winter conditions: surface currents velocity – 0.55 m/s; wind velocity = 15 m/s; significant wave height = 3m. Summer conditions: surface currents velocity – 0.25 m/s; wind velocity = 5 m/s; significant wave height = 1.5m.

a)

b)

c)

Figure 55 - Location points for the shoreline contamination risk detailed study – a) is the location in Portuguese continental map; b) is the aerial view from P1 (Praia Azul) and c) is the aerial image from P2 (Ilha da Barreta).

As can be seen in Figure 56, differences could be found when comparing both points for the same metocean conditions. The differences in risk values for both points subject to the same metocean conditions can only be explained by the different vessels in the proximity (with P1 having higher vessel traffic density in the neighbourhood), putting on evidence the dynamic response of the risk model to vessel traffic, because this is the only factor changing along the time.

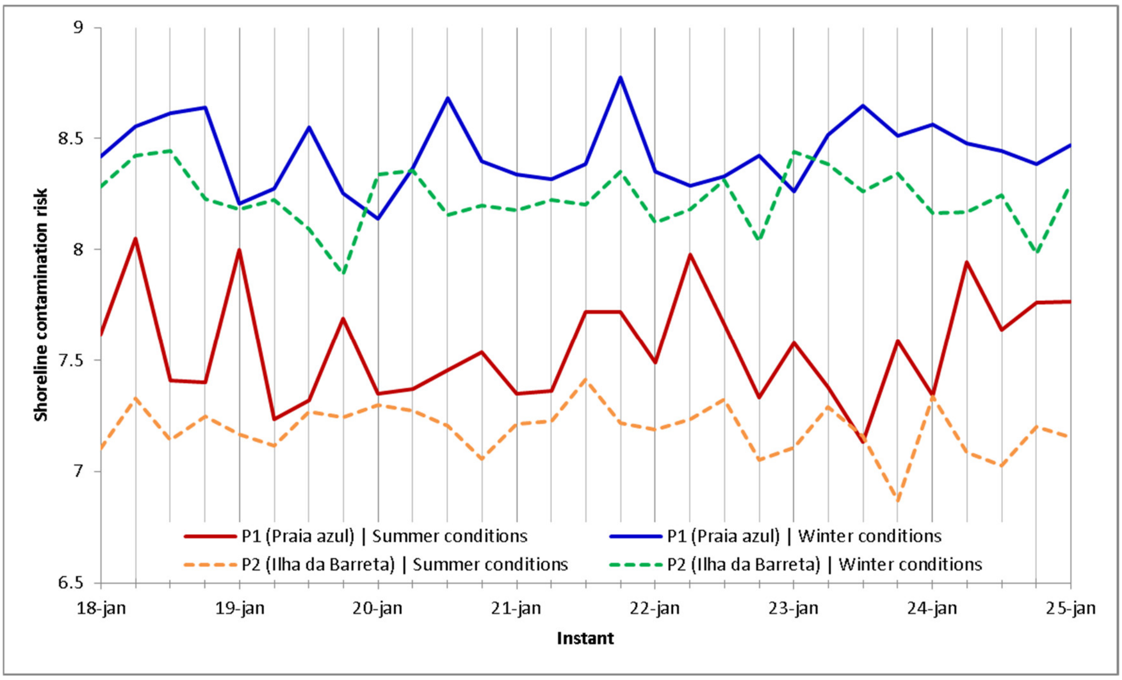


Figure 56 - Evolution of shoreline contamination risk in P1 and P2 with vessel AIS information obtained between 18 and 25th of January, 2013, and using different space and time constant metocean conditions. Winter / rough conditions: surface currents velocity – 0.55 m/s; wind velocity = 15 m/s; significant wave height = 3m. Summer / calm conditions: surface currents velocity – 0.25 m/s; wind velocity = 5 m/s; significant wave height = 1.5m.

Additionally, Figure 56 also illustrates the differences in risk values when comparing winter vs. summer conditions for the same point, justified by the response of the risk model on the metocean conditions. This aspect is further explained in the following subchapters.

Evaluating dynamic response to metocean conditions

Since the developed system is able to digest variable metocean conditions from forecasting systems, a second exercise with two simulations (winter: 18^{th}-25^{th} January 2013 and summer: 18^{th}-25^{th} June 2013) was performed for the same points, as considered in the previous study (P1 and P2), but here using metocean forecasts variable in time and space, and keeping the same variable vessel positions in both simulations (vessel's AIS positions obtained in 18^{th}-25^{th} January 2013). Both shore locations are therefore subject to different metocean conditions and different vessels in the proximity, which can affect the evolution of shoreline contamination risk along time. The metocean conditions (from the models described in section 2.5) used in both locations are illustrated in Figure 57 and Figure 58. The results from this exercise are illustrated in Figure 59.

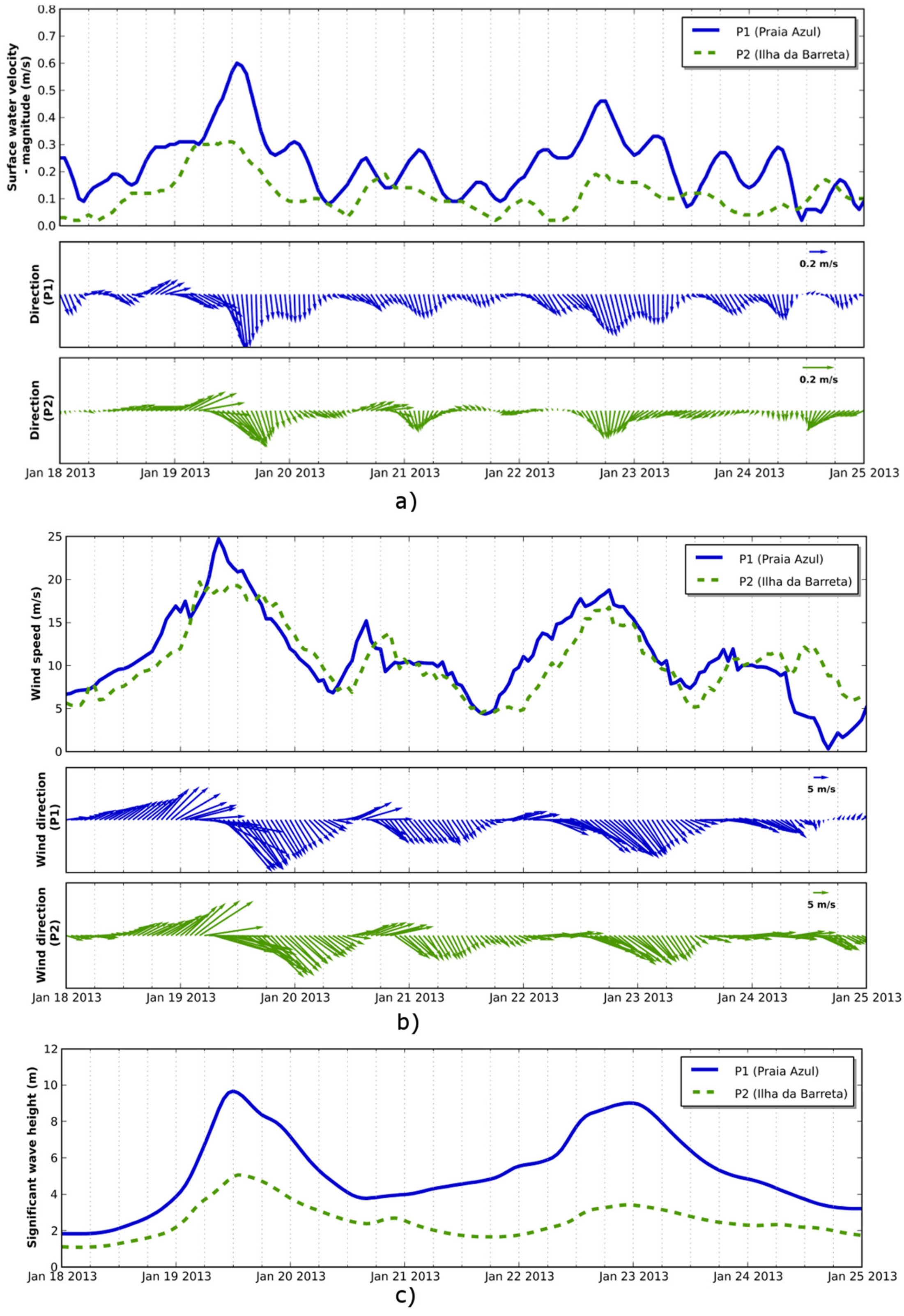


Figure 57 - Metocean conditions used in risk model, in points P1 and P2, during January. Surface water velocity, wind velocity and significant wave height.

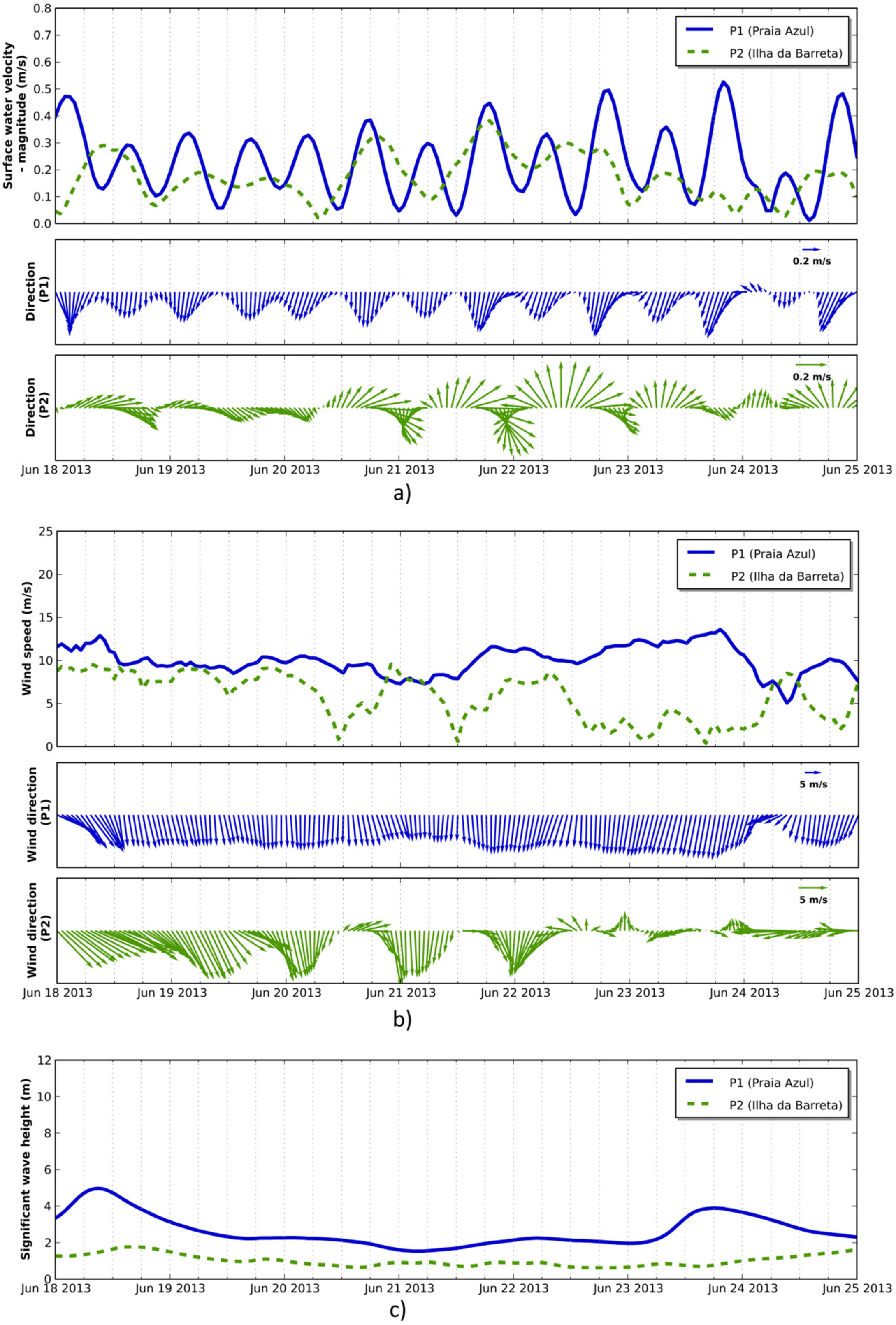


Figure 58 - Metocean conditions used in risk model, in points P1 and P2, during June. Surface water velocity, wind velocity and significant wave height.

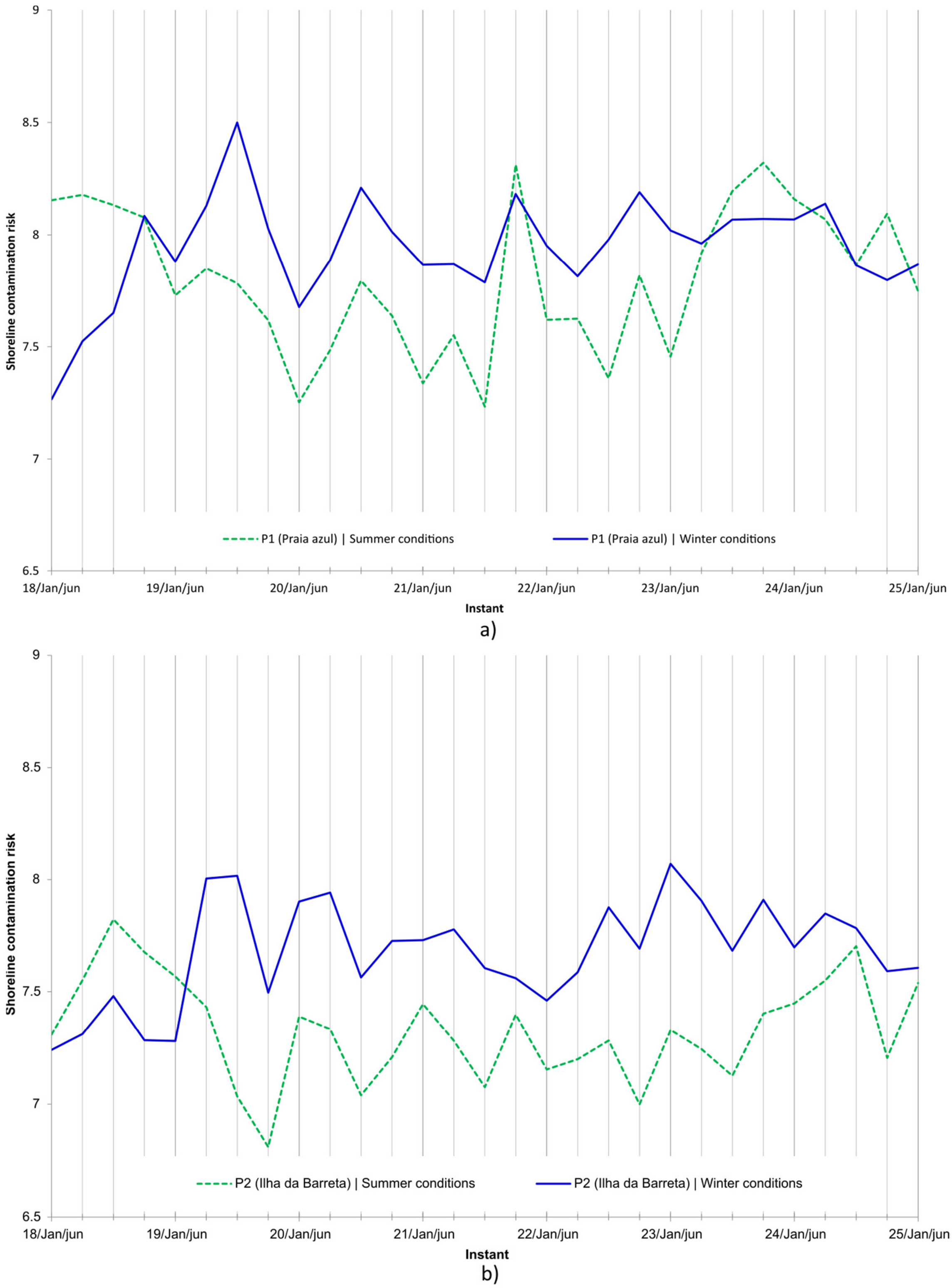


Figure 59 - Evolution of shoreline contamination risk in P1 (a) and P2 b) with vessel AIS information obtained between 18 and 25th of January, 2013, and using different space and time variable metocean conditions, illustrated in Figure 57 and Figure 58.

The temporal variations and differences between shoreline contamination risk levels in winter and summer conditions identified can only be explained by the variation in metocean model conditions, since all the other conditions were kept constant. In general, risks are higher in January for both points, as expected (due to winter metocean conditions). The obtained results show risk variations of 0.5-1 risk units in a 6-hour interval, meaning that the computed shoreline contamination risk is dynamically responding to the variations of combined effects of metocean conditions and vessel traffic. The risks obtained in P1 (Praia Azul) during the simulation periods are in general larger than in P2, because the former point is located in a site subject to rougher metocean conditions. In winter, maximum risk values are identified in 19th and 23rd of January, in agreement with the peaks visible in winter metocean conditions, in Figure 57. In summer, two strong peaks are well identified at P1, in January 21st, and January 23rd – both at 18h00. The latter one can be explained by the metocean conditions (significant wave height, wind and surface water velocity increase during that period, as can be seen in Figure 58), however the former peak is only explained by the AIS information. Moreover, this peak is also present in summer (because the same AIS information is used).

Integrated analysis in the whole pilot area

In addition to the evaluation of risk model behaviour in isolated shore locations, we performed a more complete and integrative set of analyses, considering all shore locations in the pilot area. In these analyses, the different shoreline contamination risks along the coast were integrated in the form of instant mean averages. The different 1045 shore locations along the Portuguese coast were considered. The risk model was run every 6 hours between 18-1-2013 and 25-1-2013 (winter conditions), and between 18-6-2013 and 25-6-2013 (summer conditions). The main purpose of performing these integrated analyses in the whole studied area is to obtain a more representative evaluation of the model risk behaviour.

The first integrated analysis for the whole area of study consisted on running the risk model using the same conditions as used on subchapter "Evaluating dynamic response to vessels in the proximity": constant metocean conditions in each period, in both space and time along the runs – thus with temporal evolution of the risk levels totally dependent on vessel traffic conditions. Summer scenario was run using vessel AIS information from the period between 18-6-2013 and 25-6-2013, surface currents velocity – 0.25 m/s; wind velocity = 5 m/s; significant wave height = 1.5m. Winter scenario was established with the vessel AIS information from 18-1-2013 to 25-1-2013, with surface currents velocity – 0.55 m/s; wind velocity = 15 m/s; significant wave height = 3m. The obtained mean and maximum values for the whole domain can vary more than 0.5 risk units at each time step (6h), confirming the results obtained for P1 and P2. Obtained results from this analysis are presented in Figure 60. The instant standard deviation values for the whole domain are usually around 0.5 for both runs. Most of the peaks detected in the risk mean and maximum values are around 12h00 and 18h00 for both runs, meaning that this is the daily time period where most intense traffic seems to be detected in the studied area.

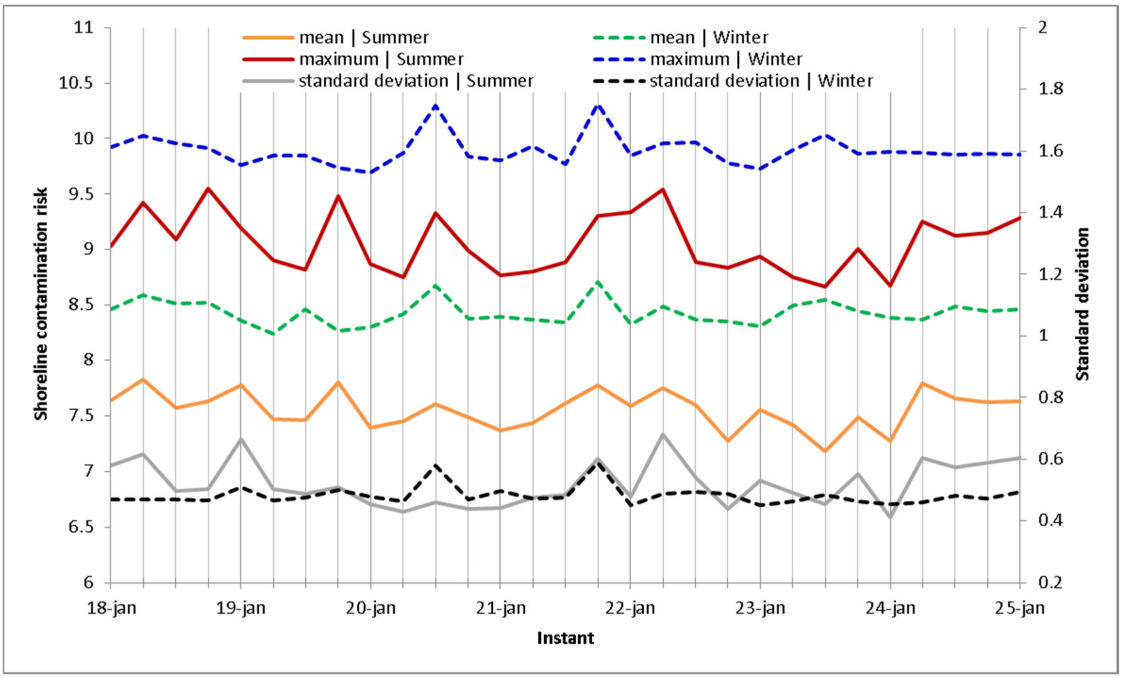


Figure 60 - Integrated shoreline contamination risk for the whole pilot area, with AIS vessel information between 18th January and 25th January 2013, and using different space and time constant metocean conditions. Winter / rough conditions: surface currents velocity – 0.55 m/s; wind velocity = 15 m/s; significant wave height = 3m. Summer / calm conditions: surface currents velocity – 0.25 m/s; wind velocity = 5 m/s; significant wave height = 1.5m.

In addition to the previously specified constant metocean conditions used, a set of 3 simulations was run for each of the selected periods (18-1-2013 to 25-1-2013; 18-6-2013 to 25-6-2013), using the exact modelled metocean solutions provided by the operational forecasting systems, and additionally increasing and decreasing those solutions in 50% for the properties that directly affect the risk level. The main purpose of this set of simulations is to obtain a more sensitive analysis of the risk methodology under different realistic conditions, assuming that the chosen modelled scenarios will cover a representative part of the marine weather situations found in the pilot area. This set of analysis can also provide a clearer idea about the thresholds of the presented tool. The results from this set of simulations are resumed in Figure 61. These images also provide information about the maximum values and standard deviation for each instant, showing the dynamic variation along the coast.

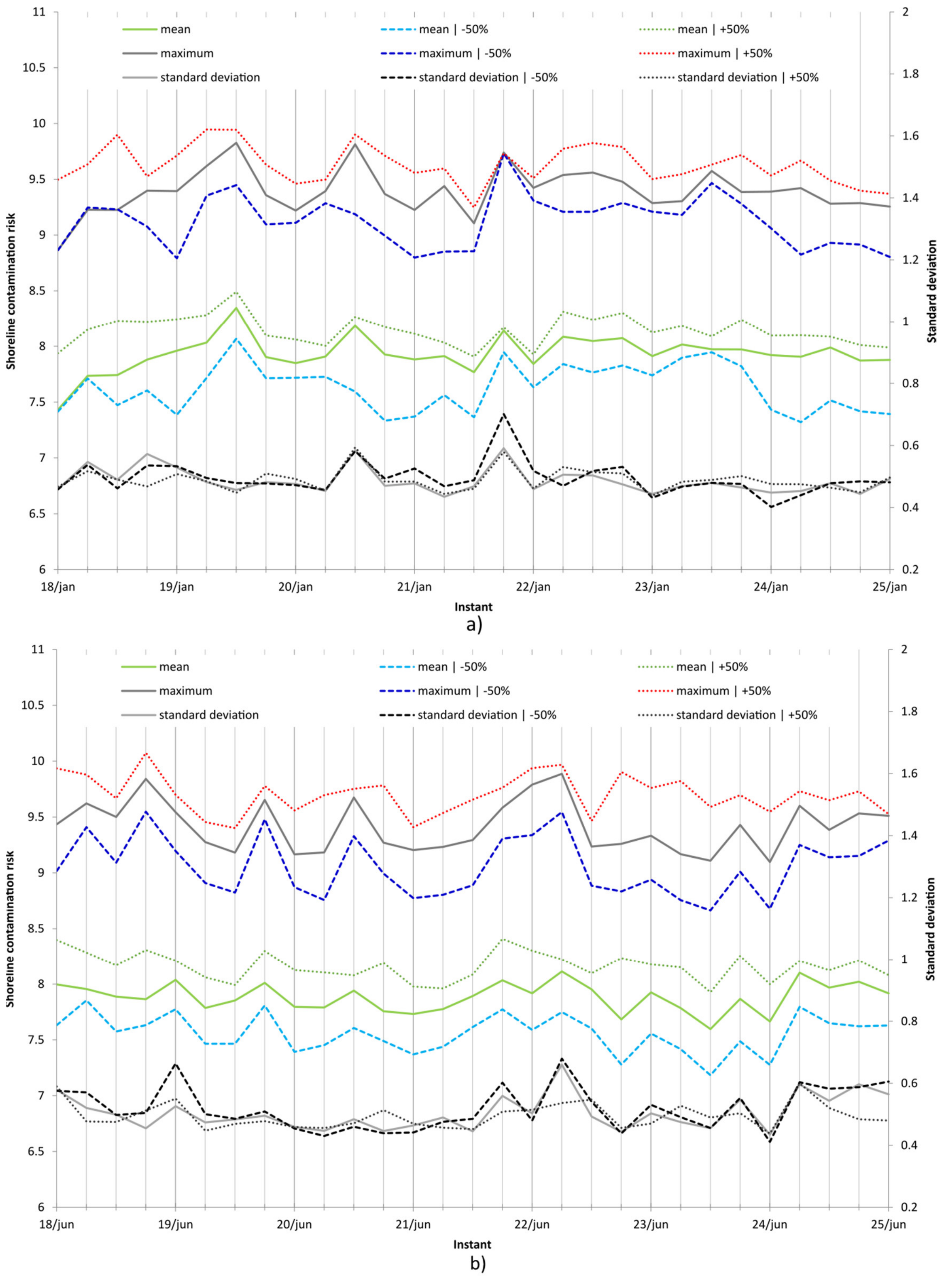


Figure 61 - Integrated shoreline contamination risks (instant mean, maximum and standard deviation) for the whole pilot area, obtained with 3 values for metocean model parameters (direct model output; model + 50%; model – 50%). AIS vessel information and metocean model conditions between 18th January and 25th January 2013 (a), and with AIS vessel information and metocean model conditions between 18th January and 25th January 2013 (b)

The rougher metocean conditions previously identified in 19th January are responsible for a peak in shoreline contamination risk for that day, in winter conditions (Figure 61a). In each of those figures (Figure 61a) and Figure 61b)), the increase of metocean parameters generates an increase on computed risk levels, both mean and maximum values in the whole domain. The increasing or decreasing of 1.5 times (50%) the metocean properties, can result in a modification of risk levels up to 0.5 risk units. Mean risk values are generally around 8 risk units, with maximum risk values of 10, which is below the critical risk threshold (12) defined in the risk matrix (Table 17). Once again, instant standard deviations are generally around 0.5 or even higher, and the obtained mean and maximum values for the whole domain can vary more than 0.5 risk units at each time step (6h), in both periods (although stronger variations are detected in January, which can also be explained by the stronger irregularity in metocean conditions for that period). These results confirm the previous analyses conducted for P1 and P2 and also for the whole domain, when using constant metocean conditions.

Comparing Figure 61a) and Figure 61b), it can also be seen that the modelled risk is not necessarily lower in the summer period, despite the calmer metocean conditions. Indeed, in the first days of the simulations, the opposite situation is verified – shoreline risk level is greater in summer. The main reason is the fact that vessel traffic was denser in the summer period, compared to the winter period (Figure 62). The records indicate an average of 677 vessel positions recorded every 6 hours, during the selected January period. In the selected June period, an average of 725 vessel positions was recorded. Therefore, after comparing the integrated risk levels between Figure 61a) and Figure 61b), it can be said that in the modelled periods, the vessel traffic assumed more importance than the metocean conditions in the determination of the risk. Actually, the simple presence of a small number of mega-tankers in the nearshore is enough to increase the risk values. This also puts on evidence the complexity of the system.

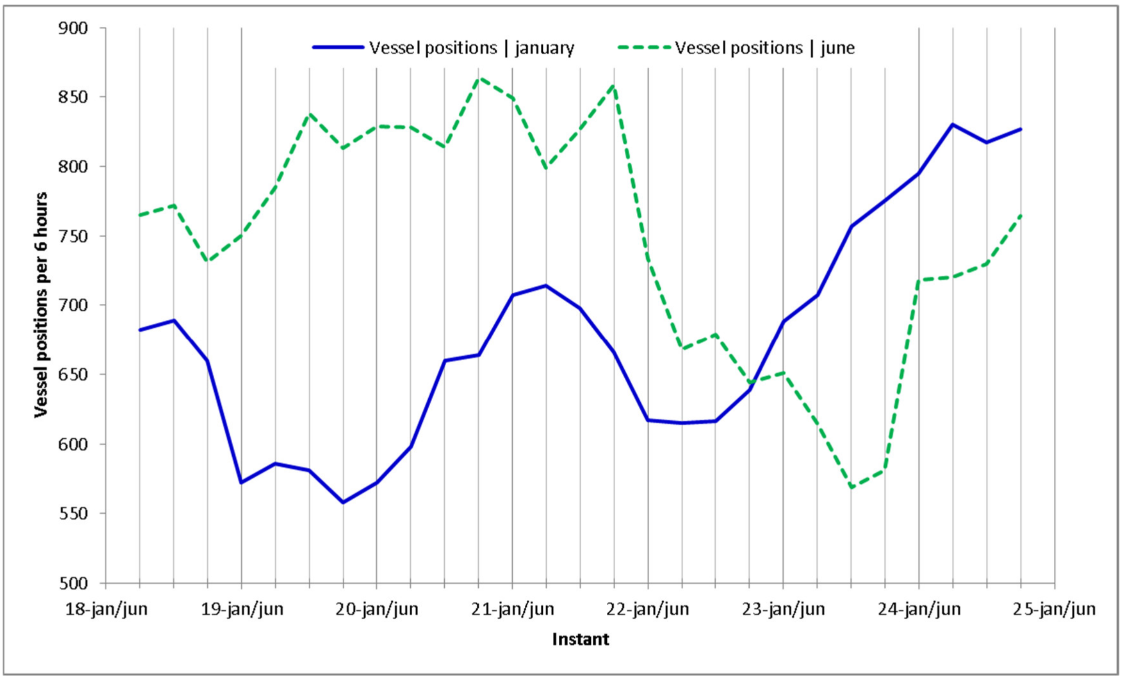


Figure 62 - Recorded AIS vessel positions per 6-hour time intervals in the pilot area, obtained in two different weeks: 18th-25th January 2013 and 18th-25th June 2013.

V.3.3.4 The role of oil spill model

The different metocean conditions directly affect accident probabilities (through correction factors), but can also influence oil weathering processes – for instance, higher evaporation rates are expected in the summer, reducing oil amount reaching shoreline, and consequently reducing shoreline risk in summer – as identified in Olita et al., 2012. On the other side, stronger wind conditions in winter can also cause a more intense oil dispersion in the water column, contributing to a lower shoreline contamination risk in winter, as expressed in Liubartseva et al., 2015. The direct influence of oil weathering processes is studied in this chapter.

Different tests were performed to evaluate the relevance of having an oil fate and behaviour spill model integrated in this risk modelling tool. Calibration tests were also performed.

Onshore vs. offshore

First, it is important to evaluate the risk model response to different environmental conditions, favourable or unfavourable to shoreline spill contamination. In that sense, two opposite environmental modelling scenarios were defined in this scope, as the basis of the exercise here proposed: the same ship position and metocean conditions were used in both scenarios, except wind direction (wind magnitude was not modified). The onshore wind scenario was set with a wind direction of 240º, favourable to transport oil to the near-shore. The offshore wind scenario was set with a wind direction of 60º, favourable to transport oil to the open ocean and far away from the coast. The risk model was then run for the whole pilot area for the two previously mentioned scenarios in different time instants along one day, and shoreline contamination risk levels for each time instant were integrated in mean values for the whole pilot area.

Since the developed risk model includes two different methods to compute the shoreline contamination risk (estimation of oil reaching the shoreline based on oil spill model – "modelled" approach; or based on ship proximity to shoreline – "non-modelled" approach), the two previous runs are also interesting to evaluate the relative dynamic response of the "modelled" shoreline contamination risk, against the "non-modelled" approach, which therefore is independent of wind or current directions (thus there is no onshore and offshore differentiation for the shoreline contamination risk computed using a "non-modelled" approach).

In addition to the three previous runs, two more runs were included, turning off the oil spill weathering processes in both onshore and offshore wind scenarios. These two runs consisted in understanding how significant is to integrate the oil spill specific weathering processes (mainly the oil spreading, evaporation, dispersion and emulsification) in the risk model, instead of simply using a generic lagrangian model.

Those five different types of shoreline contamination results (non-modelled approach; on-shore wind scenario; offshore wind scenario; on-shore wind scenario with no oil weathering processes; offshore wind scenario with no oil weathering processes) were organized in mean values, available in Figure 63.

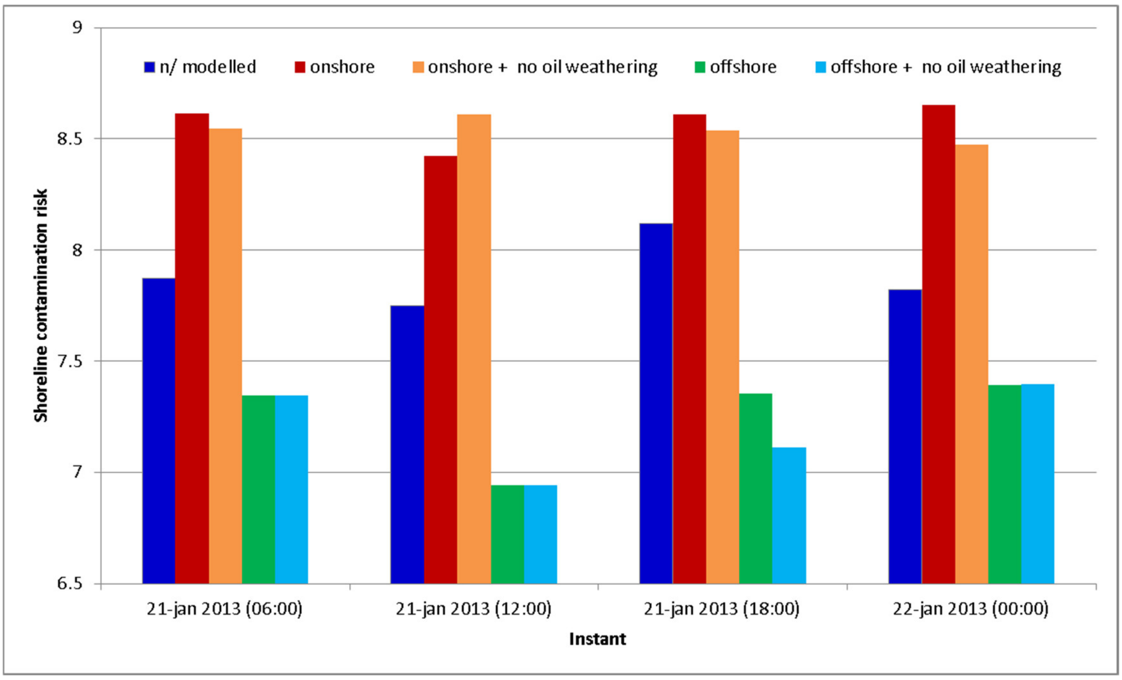


Figure 63 - Integrated shoreline contamination risk levels at different time instants from January 21st and 22nd, 2013. Results presented in mean values for the shoreline in the whole pilot area studied. Shoreline risk levels computed with 4 different approaches: non-modelled approach; modelled approach using onshore wind; modelled approach without oil weathering processes, using onshore wind; modelled approach using offshore wind; modelled approach without oil weathering processes, using offshore wind.

Results allow to firstly understand the relevance of including an oil transport model in the risk approach, mainly because it reduces the predicted risk according to favourable metocean conditions (in this case, the wind direction) – the difference between on-shore wind scenario and the others is very significant. Second, it can be seen that the developed risk model takes relative advantage of modelling the oil weathering processes, as there is a difference between onshore wind scenario with and without oil weathering processes. The default oil product used (a medium crude oil named Carpinteria) has a relatively low evaporation rate (more significant in the first hours) and almost null dispersion. However, Carpinteria has significant emulsification, potentially generating a polluted emulsion (with a high water content) with more mass than the initial oil spilt. In other words, this oil product, once spilt in water and subject to weathering processes, can increase its mass (through the incorporation of water in oil), therefore increasing the amount of pollutant reaching the shoreline, and increasing the risk of contamination when compared to shoreline contamination risk computed without oil weathering processes. This is in fact what is observed in some instants from Figure 63.

Compare different oil products

The adoption of Carpinteria as default oil product for risk modelling is indeed based on a "worst case scenario" approach, related to the environmental problems that it can pose to shoreline areas due to low evaporation and dispersion, and significant emulsification. Using other oil products in this risk model would eventually result in different risk values, due to differences in oil mass lost from the surface (to atmosphere, water column, etc.) related to oil weathering. To test the influence of different oil products in the risk model, a new set of tests with four different oil products was performed, using the previously defined environmental scenarios – onshore and offshore wind conditions.

The oil products selected have different weathering behaviour (Table 18).

Table 18 - Evolution in time of approximated oil mass lost and water content in oil (in percentage of mass) as result of the main weathering processes, in 4 oil types, under regular metocean conditions in the pilot area (wind: 10 m/s; significant wave height: 2.5m; water temperature: 15°)

Oil type	Oil weathering process	Time after spill (h)		
		6	12	24
Diesel Fuel Oil (refined)	Evaporation	61%	61%	61%
	Dispersion	39%	39%	39%
	Water content (emulsification)	-	-	-
Carpinteria (crude)	Evaporation	33%	34%	36%
	Dispersion	0.71%	0.71%	0.71%
	Water content (emulsification)	70%	72%	72%
Bunker C (refined)	Evaporation	4%	5%	6%
	Dispersion	3%	8%	15%
	Water content (emulsification)	-	-	-
Fuel Oil No 2 (refined)	Evaporation	13%	14%	14%
	Dispersion	70%	86%	86%
	Water content in (emulsification)	-	-	-

Results for onshore wind scenario are presented in Figure 64 (results from offshore wind scenario are not presented, since they show the same behaviour pattern as onshore conditions, although with lower risk values). Carpinteria keeps generating higher risk values, due to mass increase (emulsification). Bunker C fuel oil, which is a heavy fuel oil with low weathering, tends to generate risk values similar to Carpinteria. Diesel fuel oil and Fuel oil no. 2 tend to generate lower risk values, because they usually have more significant weathering processes – particularly diesel fuel oil.

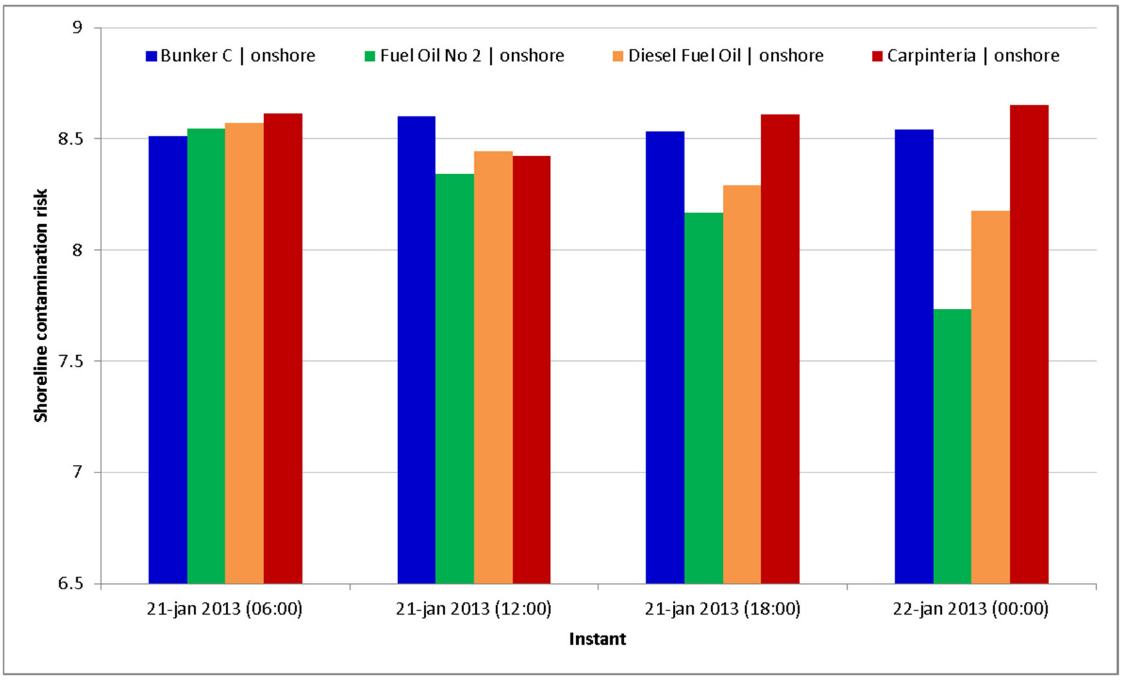


Figure 64 - Integrated shoreline contamination risk levels at different time instants from January 21st and 22nd, 2013, obtained using 4 different oil products (Bunker C, Fuel Oil no.2, Diesel Fuel Oil, Carpinteria), under onshore wind.

Calibration procedures

A side test that was implemented along the development and implementation phase was the calibration of the risk model, specifically in the adoption of the parameter shoreline stretch extension unit – L (equation 12). Increasing this value will increase the value obtained for the amount of oil reaching the coastline and the consequences in the risk model - therefore increases the relative weight of oil spill model results in the risk model. Shoreline contamination risk levels were computed using L = 100m and using L = 1000m, for both onshore and offshore scenarios. Results presented in Figure 65 show a constant increase of approximately 0.5 risk units when using L = 1000 m instead of L = 100 m. Knowing that the mean values related to non-modelled risk of shoreline contamination risk, obtained in the previous section (3.3) are usually around 8 unit values, it is considered that L = 1000 m represents a reasonable approximation, as the referred value of 8 also fits the average values obtained by both exaggerated scenarios used (offshore and onshore wind conditions). Using L = 100 m generates lower risks, even in onshore scenario. Adopting L = 100 m could therefore result in an underestimation of risk values, because we use the same risk scale as the one used for the non-modelled shoreline contamination risk.

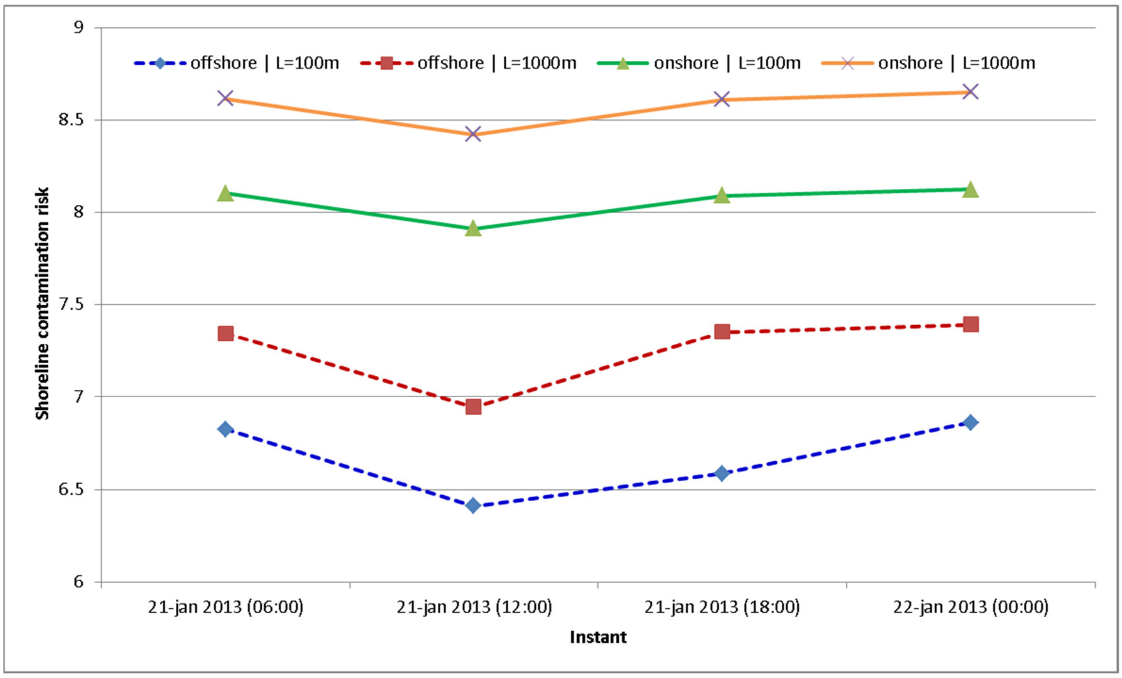


Figure 65 - Integrated shoreline contamination risk levels at different time instants from January 21st and 22nd, 2013, under onshore and offshore wind, and using different values in parameter L (shoreline stretch extension unit).

V.3.4 Discussion

The work developed in this study aimed the conceptualization, development and implementation of a novel holistic methodology for dynamic spill risk assessment from ship traffic, fully integrated with metocean and oil spill forecasting systems, and to evaluate the dynamic behaviour and response of the risk levels under different parameters. These objectives were accomplished, since the risk methodology was fully implemented in a software tool, the dynamic behaviour of the risk was demonstrated in the pilot area, and the system is being tested operationally by the authors of the project as well as the Portuguese Maritime Authority - DGAM-SCPM, allowing to be used both in real-time (providing support to monitoring activities) and on-demand situations (supporting contingency planning).

The software system here described has been designed to be easily transferable to other areas, adopting generic approaches to download specific data layers (e.g. metocean forecasting system, AIS data, etc.), and being easily user-customized in terms of risk model parameterization. The possibility of running the risk model in a central server and providing outputs to external platforms following OGC standards, increases the interoperability of the system.

The role of different variables in the risk model was presented with specific examples, with special emphasis on the relative significance of metocean, vessel traffic conditions and oil spill modelling systems integrated for the pilot area. The results from the risk modelling software tool are in agreement with what was expected from the proposed methodology for risk. Using an oil transport model (together with metocean modelling systems) in the estimation of the risk of oil reaching the coastline can provide a more robust and dynamic risk assessment. The results presented here have shown that the mere fact of having intensive ship traffic in the proximity of some coastal areas doesn't necessarily mean that the risk of shoreline contamination is high, depending on the instantaneous metocean conditions. If they are favourable to transport an eventual oil spill to offshore, the risk of shoreline contamination will be low. Also, it was shown that even if the metocean and the sea state conditions are stable and not extremely rough (reducing the probability of having ship accidents) – the risk of having ship incidents may not be necessarily reduced, depending on a combination of multiple dynamic factors, including the ship traffic intensity.

The results obtained from the sensitive analysis to different metocean conditions suggested that the correction factors in terms of probability could eventually be intensified in the future, in order to increase the relative weight of metocean conditions in the risk model, and therefore the dynamic risk change based on marine weather conditions.

The inclusion of oil weathering processes in the determination of shoreline contamination risk generates differences in risk values, depending on the oil product considered in the risk model. By default, the risk model uses an oil product that represents a worst-case scenario for the shoreline (low evaporation and dispersion; high incorporation of water through emulsion). Calibration tests in risk model were also pursued, in terms of consequences (e.g. increasing the relative weight of oil spill model results in the risk model), in order to improve and fine-tune the expected results.

Since during all the results presented in this work (including conditions very favourable to shoreline oil pollution, calm and rough metocean conditions), the mean and maximum risk values tend to be below the critical risk threshold defined in the risk matrix presented in Table 17 (critical risk values are between 12 and 16), the predefined risk matrix may be adapted in the future to better adapt to the minimum and maximum values detected in the pilot area. In parallel, less relative weight to the coastal vulnerability indices can be studied, in order to increase the amplitude and dynamic component of the risk, associated to vessel traffic, metocean conditions and oil spill weathering model.

Additionally, it should be noted that the results investigated in this study were mainly focused in the testing and evaluation of the risk model dynamic behaviour and response to the different variables, and somehow comparing amplitude of risk values along the pilot area. The evolution of risk values along time for longer periods was out of the scope at this stage. This type of study is expected to be pursued in the future, for the same pilot area included in this work.

Independently of the methodology developed and the results achieved with this study, a number of assumptions, limitations and lack of data were identified as relevant for improving the risk model:

- Using frequency constants to estimate probability of having incidents may need continuous and periodic update, because the continuous changes in the ship industry (e.g. obligation of double hull ships, mega-tankers, maritime surveillance, etc.) can change the probability of having incidents.
- The coastal vulnerability indices included should also be continuously updated and reviewed to reflect the present situation in terms of environment and socio-economic aspects of the coast.
- Several research work has been developed for estimating the probability of ship-to-ship collisions using more complex approaches (e.g. Silveira et al, 2013), however these algorithms were not included yet in this risk model.
- Heterogeneous spatial resolutions were considered for the different variables used in the risk model. We have assumed that the computed risk index resolution is equal to the coastal vulnerability (which has a high resolution - 200m or less - allowing responders to properly visualize, manage and prioritize different shoreline areas), but we have in mind that a better spatial resolution of the metocean models would potentially improve representation of the coastal processes and consequently, the risk model. The software tool is ready to accommodate more metocean models with higher spatial resolution, which can be particularly interesting when studying or monitoring the risk levels at a local scale (e.g. in a Port and its neighborhood area). Nevertheless, as a first dynamic

implementation and for the regional purpose of this work (focused on the Portuguese / Western Iberian shelf), we consider that the proposed approach is capable of demonstrating and providing satisfactory results. Moreover, the included metocean models have been previously reported as valid for studying coastal processes and coastal management support (Mateus et al., 2012; Trancoso, 2012; Franz et al., 2014).

- In the risk model adopted, there is no differentiation between identical ships from different countries, inspected at different ports, constructed or managed by different companies, or with different number of deficiencies detected in the recent past. This information is presently available online through EMSA's THETIS system, and in the future can be seen as a relevant added value for integration in the risk model, if possible.
- The actual volume of contaminants, and product type transported by each ship is not included in the risk model, since the information is not publicly available (an approximation based on ship type and dead weight tonnage is adopted). This information would be rather important to improve the realistic quantification of estimated risk.
- No risk acceptance or tolerability criteria was defined in the present risk model. The future definition of these tolerability criteria will facilitate the adoption of mitigation measures in case of unacceptable / intolerable risks detected.

Aside from these identified considerations, the work presented here opens interesting opportunities for the future both in terms of risk planning and monitoring activities. A tool like this can improve the decision support model, allowing the prioritisation of individual ships or geographical areas, and facilitating strategic and dynamic tug positioning. The possibility of being used for past or hypothetical scenarios may provide an interesting tool not only for identifying "hot-spots" in terms of shoreline contamination risk, but also to estimate future situations like the increasing of ship traffic or the size and cargo transported by the ships. Furthermore, the same risk model approach can be considered in the future to estimate other types of environmental threats, including impacts from spills in offshore platforms, impacts from onshore activities and industries involving discharges to the water environment, or even the environmental impact of maritime transport emissions on coastal air quality.

V.3.5 Acknowledgements

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The authors thank Francisco Campuzano for the development and maintenance of the hydrodynamic and wave modelling systems, as well as to Rosa Trancoso for the development of atmospheric model, and Jorge Palma for its operational maintenance. The authors want also to thank MarineTraffic for the cooperation and provision of AIS data support in the scope of ARCOPOL PLUS project. Last, but not least, a special thanks to Portuguese Maritime Authority (DGAM-SCPM) for the cooperation and support in beta testing.

V.4 Assessing oil spill risks from vessels in the Portuguese continental coast using a holistic modelling approach

Abstract

The Portuguese continental coast is constantly crossed by multiple vessels carrying pollutants or dangerous substances. Simultaneously, this coastal region assumes particular relevance in terms of ecological marine resources, as well as an increasing relevance associated to the sea resources and industry in the Portuguese socio-economics context. Here we present a comprehensive study and characterization of the risk of oil spill accidents from vessels in the Portuguese continental coast following a holistic approach answering the previously identified aspects, and benefiting from previous research work developed by the author. The risk analysis uses realistic marine weather conditions estimated by existing numerical models, and ship AIS data from the year of 2013. Metocean conditions have direct influence on the likelihood of having oil spills, as well as statistical data on past ship accidents. The consequences are quantified based on the amount of oil that can eventually reach the coastline, and its sensitivity. This coastal sensitivity includes high resolution environmental and socio-economic sensitivity indices. Based on a) the variable vessel information, b) the variable metocean conditions for the different time instants; and c) an advanced oil spill fate and behaviour model, multiple oil spill trajectory simulations are continuously run and processed in order to estimate and quantify the areas affected. In addition to the hindcast analysis during 2013, different possible future scenarios are also studied, namely the increase of the vessel tonnage, and climatic changes on metocean conditions. Statistic parameters are analysed to identify spatial and seasonal variabilities, allowing to estimate "hot spots" with the highest risk, as well as the local and global seasonal evolution of the risk, not only in typical present conditions, but also in the future or in extreme situations. The results obtained for the reference situation show the highest risk of coastal contamination in the south-eastern Portuguese coast.

This study can represent a valuable instrument to help authorities in adopting strategic measures to mitigate and control to the risk in some specific areas.

V.4.1 Introduction

The Portuguese continental coast is a busy corridor for shipping transport. Annually, approximately 75000 vessels cross the Portuguese coast, with 20% of them carrying pollutants or dangerous substances (Diário de Notícias, 2015). An average number of 600 ships of all types are instantly present in the studied area, according to MarineTraffic, 2017.

This coast is crossed by important international shipping routes with most of the maritime traffic circulating between Mediterranean Sea and Northern Europe or American Continent (Silveira et al., 2013). Oil spills (even if small) seem to be frequent on the area of study, having in mind the high number of remotely detected oil slicks, through the EU operational service CleanSeaNet, operated by EMSA – European Maritime Safety Agency (Fernandes et al., 2017a) (see Figure 66).

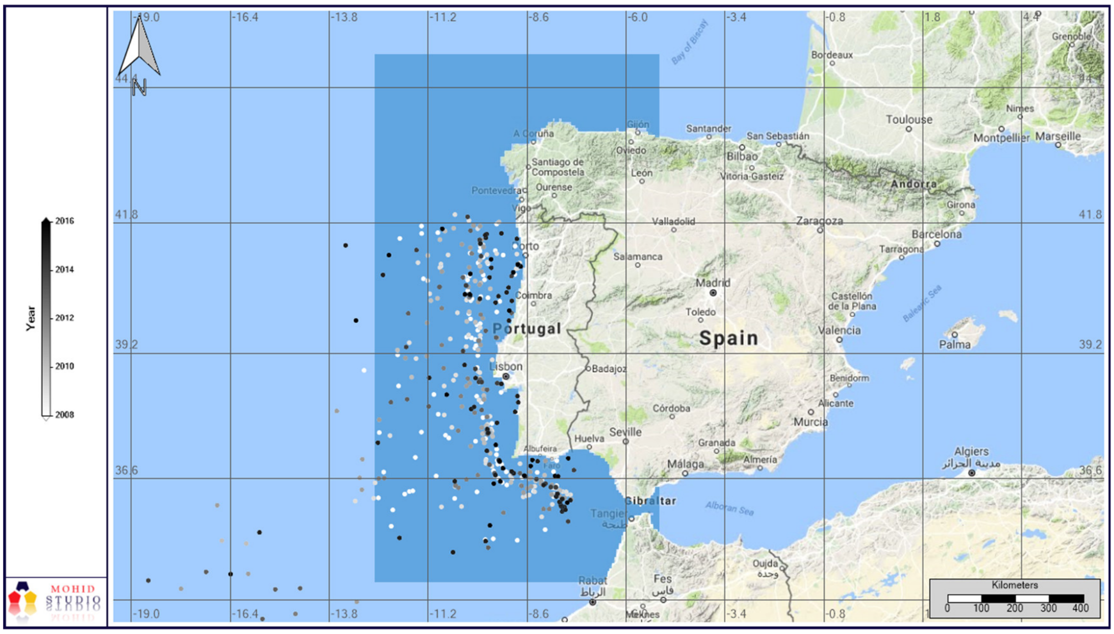


Figure 66 - Map with area of study (Portuguese continental coastline and adjacent area - in dark blue) and oil slick detections by CLEANSEANET in the Portuguese EEZ between 2008 and 2016

The sea is one of the Portuguese economy's main assets. The activities in the near-shore area assume a very relevant role in the social, environmental and economic context (vast potential in natural resources, fishing, aquaculture, maritime commerce and port activity, shipbuilding and repair, research, leisure, sports and tourism activities).

Indeed, this region is characterized not only by important and sensitive ecological marine resources, but also by an increasing relevance of the sea as a central point in the Portuguese socio-economics (with number and revenue of tourists growing annually more than 10% in the last 5 years, according to Banco de Portugal – AICEP, 2017), and with tourism sector representing approximately 50% of the total employment related to maritime activities (DGPM, 2012).

Following the evolution registered in the last years (UNCTAD, 2017(a)), the maritime transport and trade is expected to continue to grow in a general way, particularly in terms of the vessel sizes and capacity, increasing the seaborne trade in cargo per navigated mile (Lloyds Register, 2013; UNCTAD, 2017 (b)), and thus improving shipping efficiency.

All the previous aspects contribute to raise the awareness in terms of safety of navigation as well as in preventing or being prepared for marine pollution. Effective contingency planning can be improved with reliable and realistic risk assessment. Rather than looking for reactive risk assessment (based in actual spills), in this work we look for the application of a pre-emptive risk assessment methodology. Several studies stress the importance of this approach (Fernández-Macho, 2016).

A multitude of novel methodologies have been recently developed in different regions of the globe, for the assessment of oil spill risks in coastal areas (Fernandes et al., 2016a; Fernández-Macho, 2016; Valdor et al., 2016; Neves et al., 2016; Azevedo et al., 2017; Shami, 2017). Looking specifically for Portugal, the studies applied in the whole Portuguese coast, for the risk of vessel-based oil spill shoreline contamination (e.g. Silveira et al., 2013), have not properly considered holistic approaches, in the sense that didn't consider simultaneously all the aspects involved: representative metocean conditions, representative and realistic ship traffic and ship data, the probability of having accidents (depending, among other things, in metocean conditions), specificities and heterogeneity of the Portuguese coastal sensitivity (in multiple aspects, including generic environmental sensitivity to oil spills but also socio-economic and ecological aspects), and realistic identification of potential shoreline areas affected (which is only possible with adequate oil spill fate and behaviour modelling).

In the meanwhile, some valuable studies integrating multiple data (including numerical modelling) have been recently developed and applied in specific areas of the Portuguese coast, although spatially or timely limited, i.e., they assess the risk in a limited Portuguese region and / or in a limited period of time. In detail, one of the studies (Azevedo et al., 2017) is applied on a high-resolution analysis in a relatively limited area – the Aveiro lagoon – and doesn't consider ship traffic in the risk model (reducing the reliability in terms of quantification of accident probability); other study (Neves et al., 2016), although using vessel data, uses only one month of vessel traffic positions, characterizes the risk in the region of Algarve (South of Portugal), assuming constant coastal sensitivity along each coastal municipality, and using a low grid resolution (1/4º) for the oil spill model simulations.

Hence, a comprehensive and holistic oil spill risk assessment covering the whole Portuguese continental coast is still missing, taking in consideration not only numerical modelling, but also the best available coastal sensitivity indices, as well as valid information and extensive data related to vessel traffic. The ultimate purpose of a study like this is to provide a valuable instrument and results to support national authorities and environmental risk managers in terms of strategic planning and operational / tactical management in oil spill incidents, including tug positioning, definition of ports of refugee, maritime traffic surveillance and coastal monitoring, and tactical prioritization.

We consider that the versatility of the risk methodology and tool developed in Fernandes et al., 2016a fits the desired purpose. This system has already proven the potential for real-time application as a monitoring system - but in this work, we intend to analyse and assess past periods or virtual scenarios. Indeed, this dynamic risk tool allows not only to obtain a generic overview and a local characterization of the present environmental risk associated to oil spills (using representative conditions from past situations), but also to draw and analyse virtual scenarios related with foreseen long-term modifications on environmental (climate change) and vessel traffic conditions (size of the vessels).

After the present introduction and brief literature review on risk assessment applied in the Portuguese continental coast, the next Section describes the adopted methodology, assumptions and materials used. Section V.4.3 illustrates and details the obtained results under the different conditions, methods, and materials used. These results are then further discussed in Section V.4.4.

V.4.2 Materials & methods

In this work, we assess the risk of oil spill shoreline contamination in the whole Portuguese continental coast, applying a holistic and dynamic methodology as presented in Fernandes et al., 2016a.

The risk assessment framework is configured and visualized by the Graphic User Interface MOHID Studio (Bentley Systems (a)). This interface exchanges information with a desktop application server - ACTION Server (Bentley Systems (b)), which loads, downloads and updates the data from the different data sources, manages the MOHID oil spill model, processes all the information (and computes risk levels) and stores the data in a database (Figure 67).

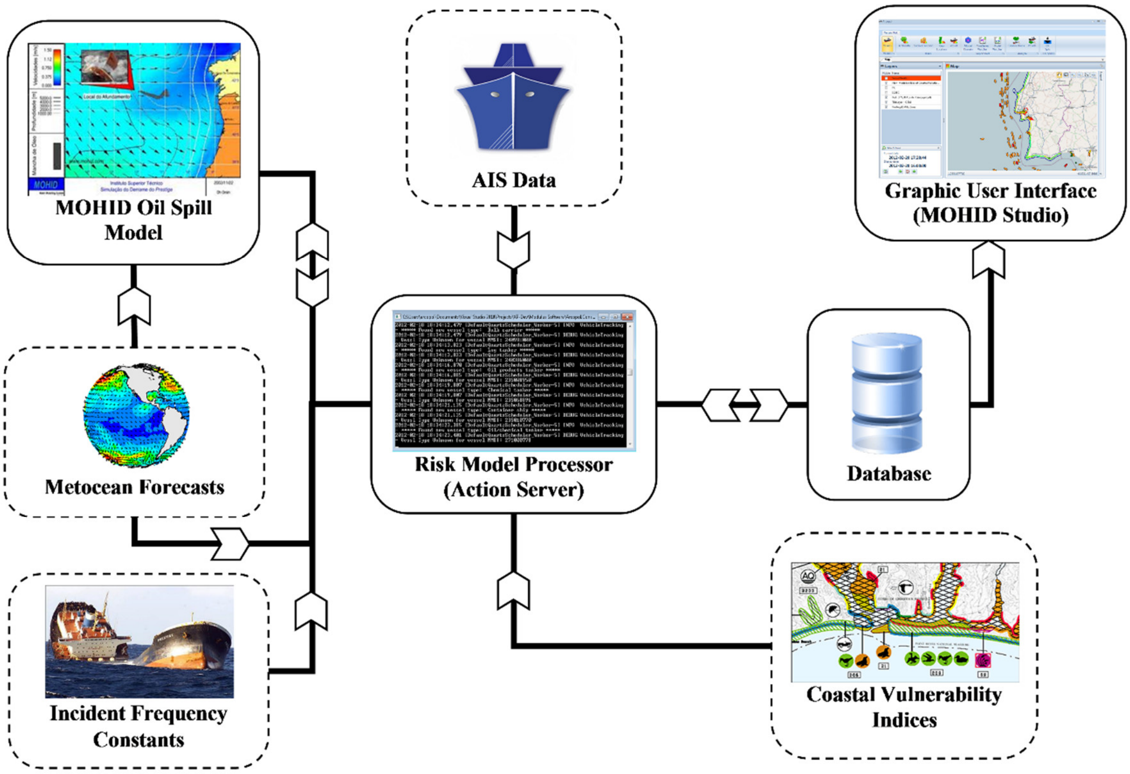


Figure 67 - General information workflow in the risk modelling system (source: Fernandes et al., 2016a)

This methodology has already proven the potential for real-time application as a monitoring system. However, the objective of this study is not focussed in real-time monitoring. The objective is not only to map, rank and compare the risks in the Portuguese coast with recent and realistic scenarios, but also to understand the risk evolution and possible future trends in the next decades, based on ship industry evolution and climatic changes. This article measures the relative risk from marine spills experienced by coastal regions in Portugal, making it possible to compare and rank each region's marine spill vulnerability with respect to the rest of regions in the target area.

The following sub-chapters detail the adopted methodology, assumptions and materials used in the study (the full risk methodology and equations are presented in Fernandes et al., 2016a).

V.4.2.1 Risk Algorithm

The method proposed for quantification of risk combines the likelihood of an oil spill occurring from a vessel navigating in the study area with the assessed consequences to the shoreline, where risk is the product of the probability (or likelihood, or frequency) of oil spill accidents from maritime traffic, times the severity (or consequences) of the events:

$$Risk = Probability \times Severity \quad (1)$$

Governed by the previous expression, different types or risk levels are determined:

- the individual risk of oil spill accident for each vessel (hereinafter called vessel accident risk), depending on the vessel itself and on the metocean conditions, which is not dependent on the coastal consequences (Figure 68);

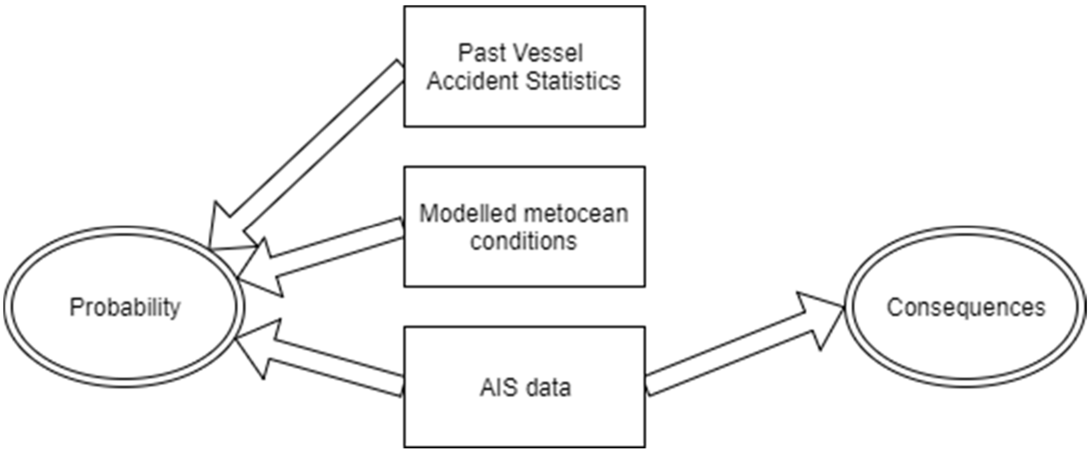


Figure 68 - Flowchart diagram for the estimation of the vessel accident risk

- the risk of shoreline contamination taking into account coastal sensitivity indices with the integration of the above risks of oil spill accidents of all the vessels present in the vicinity of a given coastal stretch. To account for the potential consequences and amount of oil reaching shoreline, two strategies are implemented and evaluated:
    - o a non-modelled one (hereinafter called non-modelled shoreline risk) based on a correction factor that is function of the distance between the vessel and the coast stretch (Figure 69).

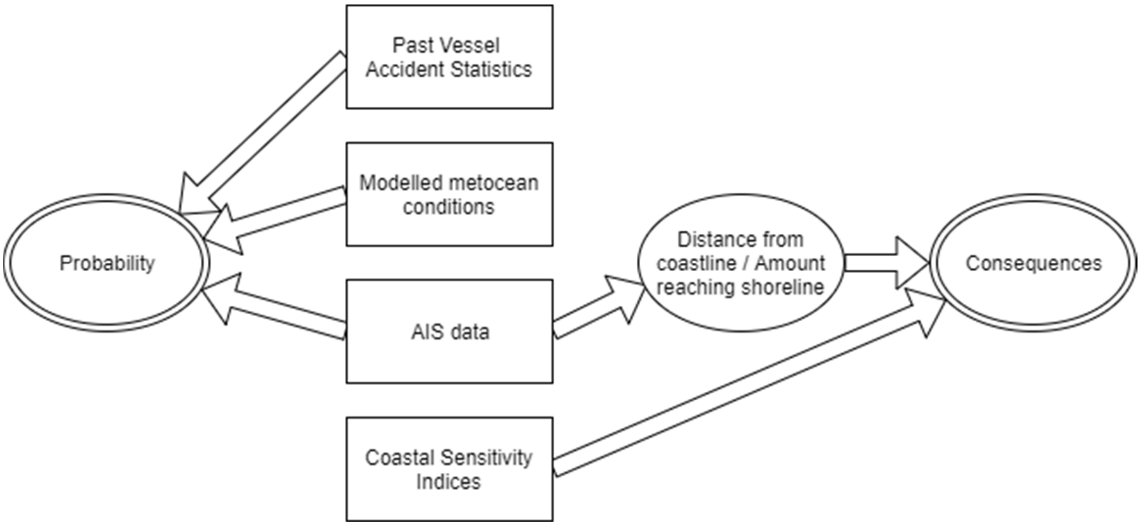


Figure 69 - Flowchart diagram for the estimation of the non-modelled shoreline risk

- a modelled one (hereinafter called modelled shoreline risk) using an oil spill transport and behaviour spill modelling for each vessel (Figure 70);

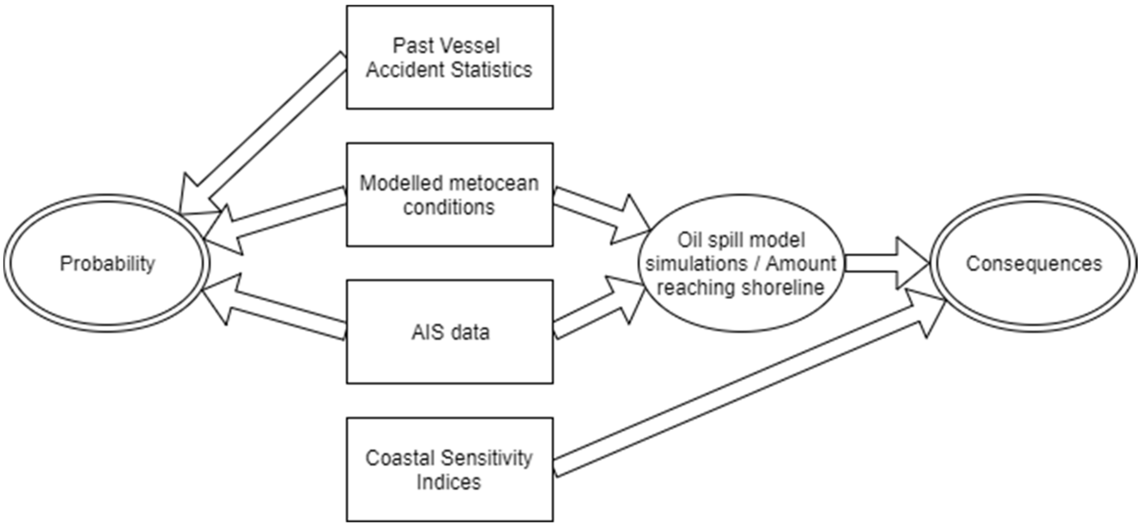


Figure 70 - Flowchart diagram for the estimation of the modelled shoreline risk

The modelled shoreline risk – the most integrative and holistic risk level adopted - takes in consideration all the following multiple information layers:

a) instant vessel information (AIS), including position, velocities, vessel type and dimensions (velocity has direct influence on likelihood; dimensions have direct influence on severity; vessel type influences both likelihood and severity; position is used for selecting corresponding metocean conditions, to run oil spill simulations, and to identify the distance from the coast – this latter aspect will influence not only the likelihood, but also the severity in non-modelled shoreline risk)

b) regional statistics information on vessel's accidents history (contributes to likelihood),
c) instant metocean forecasting data (direct impact on likelihood, and indirect impact on severity of modelled shoreline risk, as these conditions control the trajectory and behaviour of spilled oil),
d) high resolution coastal sensitivity indices (direct influence on severity of both modelled and non-modelled shoreline contamination risks),
e) amount of oil reaching shoreline as a result of continuously simulated oil spills from the ships along the coast (direct influence on severity of modelled shoreline contamination risk).

Thus, the non-modelled shoreline risk is quite similar to the previous one, but doesn't include the e) factor (which, as already mentioned is replaced by a distance-related correction factor). The vessel accident risk is therefore only dependent on the a), b) and c) factors.

As already mentioned, all the details (including equations and assumptions) related with this risk methodology are fully described in Fernandes et al., 2016a.

V.4.2.2 Coastal severity

The quantification of the potential severity or consequences associated to shoreline contamination by oil spills from vessels is dependent not only on a proper mapping of the affected areas (based on the amount of contaminant that reaches ashore), but also on the degree of loss resulting from the contamination, which is determined by the characteristics of the potentially affected shoreline, i.e., the coastal sensitivity.

The final shoreline severity used for the risk indices will depend 50% on the potential amount of oil that reaches the coastline, and the others 50% on the combination of coastal sensitivity indices.

Coastal Sensitivity

Different studies in Portugal have been able to generate and apply multiple methodologies for coastal sensitivity. However, some of those studies are not adequate for this study: some of them don't cover the whole continental coast of Portugal; others have very low spatial discretization (e.g.: each shoreline segment corresponding to the municipality coastline), limiting the purpose of the study. Having this in mind, the coastal sensitivity indices presented in Fernandes and Santos, 2017c fit the purpose of this work: they were obtained with a high degree of variability (based on the geomorphologic type of coast); they cover the whole Portuguese continental coast (and in fact, the same methodology was already applied in Madeira under the scope of MARPOCS project), and they were recently updated.

The coastal sensitivity indices are split on three different types: coastal sensitivity index (ranking based on the physical or geomorphologic type of coast; from 1 to 10, adopting the same approach as NOAA's Environmental Sensitivity Index); socio-economic sensitivity index (based on objective statistical indicators related to population, fisheries and aquaculture, recreational activities, coastal tourism; ranking varying between 1 and 5); and ecological sensitivity index (based on regions with marine protected areas; ranking varying between 1 and 5). Full details on the methodology and implementation of these indices in the Portuguese coast can be found in Fernandes and Santos (2017c).

Although these indices have different ranks (1-10 or 1-5), they are modified to have the same relative weight in the determination of the severity (since coastal sensitivity index is between 1 and 10, its value is divided by 2).

Amount of contaminant reaching ashore

The estimation of the severity considers different amounts of oil available for spillage (i.e., potentially released in case of an accident) based in the specific vessel type and tonnage: more oil available for spillage means higher severity index. In a spill incident situation, that amount of oil may or may not reach ashore, depending on the multiple conditions that will influence the fate and behaviour of the spilled oil at sea (which can be estimated by an oil spill model). The severity, and as a consequence, the shoreline contamination risk, will be thus directly influenced by the potential amount of oil reaching ashore.

In the case of non-modelled shoreline risk, no oil spill model is taken in consideration - a vessel shoreline proximity correction factor is subtracted to the severity of spill incident (with this correction factor decreasing as the vessel approaches the coastline). In other words, the severity (and the shoreline risk of contamination) will increase as a vessel approaches the shoreline. This approach is obviously limited, because a vessel can leak oil in the nearshore, and it doesn't mean that the coastline will be polluted. It will all depend on the metocean conditions and how they will contribute to bring the oil ashore.

Because of the limitation mentioned above, a modelled shoreline risk approach is also considered. In this case, instead of considering an amount of oil available for spillage and a proximity correction factor for the determination of severity, as previously referred, the risk model estimates the amount of oil that reaches nearshore (a threshold of 1000m was considered as the default nearshore classification, which means that only the amount of oil closer than 1000m will be considered) in each shoreline segment in the following 24 hours, and uses that information directly for the determination of severity. Figure 71 shows a map with the 24-hour integrated oil particle positions (100 particles per emission) considering multiple oil spill emissions (314 emissions in this simulation) based on the instant vessel positions. This is the type of data that is used from MOHID oil spill model to identify the amount of oil reaching nearshore, in the estimation of instant modelled shoreline risk.

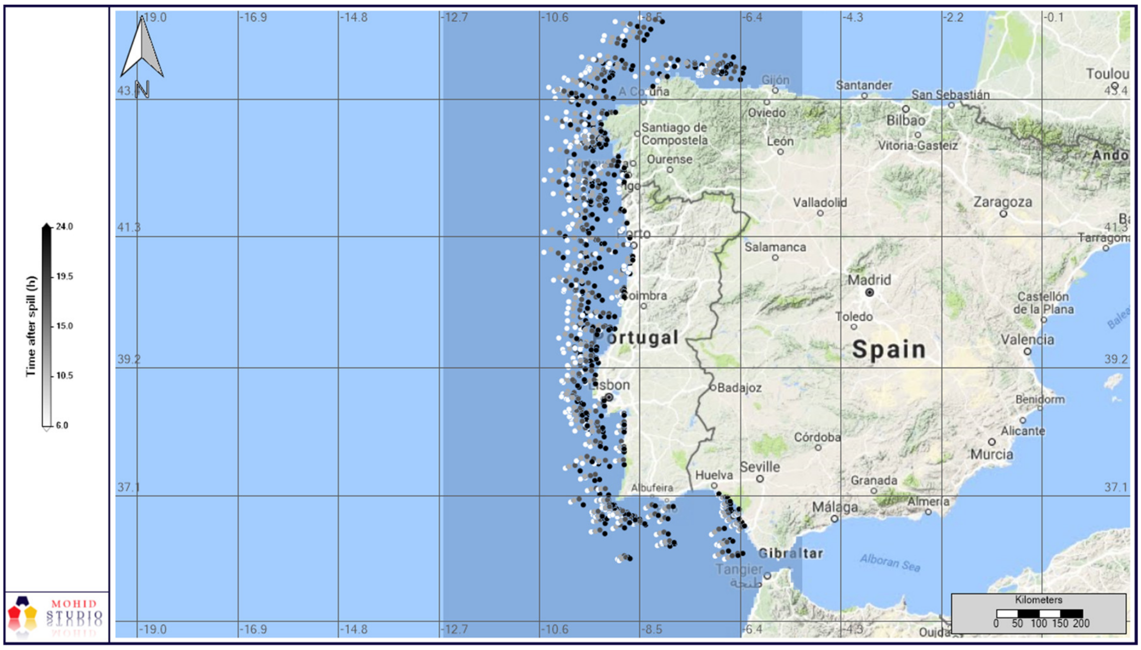


Figure 71 - map of 24-hour integrated oil particle positions in 2013-02-27. Emissions (314) based in the instant vessel positions.

The amount of oil reaching the nearshore is computed using the most recent version of MOHID oil spill model (Fernandes et al., 2017a), widely used in real cases, studies and research applications. This model follows a lagrangian approach, which estimates the pollutants behaviour assuming that the oil can be represented by a cloud of discrete particles (or super-particles) advected by wind, currents and waves (including Stokes drift), and spread due to random turbulent diffusion or mechanical spreading. This oil spill model is freely available for public access, since it is integrated in MOHID numerical modelling system which follows a FOSS (free / open source software) strategy.

The metocean conditions (wind, currents, waves) are ingested "offline" by the system. The oil spill model is run with all the weathering processes connected. The oil product named "Carpinteria" was adopted as default oil product for the simulations, and the selection was based on a "worst case scenario" approach, related to the environmental problems that it can pose to shoreline areas due to low evaporation and dispersion, and significant emulsification. Using other oil products in this risk model would result in different risk values, due to differences in oil mass lost from the surface (to atmosphere, water column, etc.) related to oil weathering, however, previous sensitivity tests (Fernandes et al., 2016a) have shown that indeed this product is one of the worst cases to be considered in terms of environmental pollution.

The computational mesh used for the oil spill simulations is the same as used for the hydrodynamic model (around 6 km).

V.4.2.3 Considered scenarios

Two different risk assessment approaches were performed: one is focussed on the reproduction of a historic scenario - the whole year of 2013.The second type of analysis intends to study the evolution of the risk of oil spill contamination assuming expected long-term future scenarios – in particular, for this study, two different scenarios were considered: the increase of vessel dimensions and climate change consequences.

In the hindcast assessment, the main objective is to characterize the typical risk in the Portuguese coast, assuming that the metocean and the vessel traffic conditions in 2013 can be representative in terms of climatological situations in the area of study.

For the analysis related with long-term future scenarios, the selected conditions (increase of vessel dimensions; climate change consequences) took in consideration the same conditions applied for the year of 2013, but with modifications on key-parameters that would be expected to change in each considered scenario. Thus, in the case of the scenario related with the increase of vessel dimensions, the property DWT (deadweight tonnage) was increased (more details in chapter V.4.2.4). In the case of climate change scenario, the significant wave height was modified (more details in chapter V.4.2.5).

Although vessel data exists with an update frequency of 3 hours, a preliminary comparison between the risk levels obtained with a 3-hour time step didn't show significant differences to the 6-hour time – therefore, the risk levels adopted in this study are computed every 6 hours. This approach allowed to reduce computational efforts in the course of this work. As a reference, in a good laptop, the risk modelling system needs one day to compute one month for the modelled shoreline contamination risk (which continuously uses oil spill model to quantify the fraction of oil reaching shoreline as a result of virtual spills from vessels). The non-modelled shoreline contamination risk (instead of running the oil spill model, the system considers the distance between the vessel position and the shoreline point being computed) needs only one hour to simulate the same month. An average number of 250 virtual oil spills (the number changes, as a function of the number of vessels located in the area of study) involving 100 particles per spill simulation, are run in each time instant (every 6 hours), which means that for a whole year, more than 365 000 oil spill simulations and 36 500 000 lagrangian particles are processed.

V.4.2.4 Dynamic and static vessel data

The study uses the dynamic vessel AIS information for the complete year of 2013, obtained with an update time frequency of 3 hours. These data were obtained from a global ship tracking intelligence data provider (MarineTraffic) (Figure 72).

The used vessel parameters are the geographical position, cargo type, speed, vessel type, weight (DWT), name and ID (MMSI and / or IMO number). Vessels with less than 100 DWT, passenger vessels and fishing vessels navigating outside restricted waters are not considered in this study. It is assumed that a vessel is navigating in restricted waters if distance to shoreline is not greater than 3 nautical miles, or if water depth is not deeper than 20 meters.

In addition, static information relative to the types of vessel (statistical information in terms of historic frequency of vessel accidents per nautical mile navigated) is also taken in consideration, for the improvement on the quantification of accident probability. All the details relative to the frequency constants used are described in Fernandes et al., 2016a.

In the scenario related with the future trends on maritime transport, the same AIS data is used (thus we don't modify the ship traffic density), except the DWT which is increased by 100%, based on the analysed information from studies compiling the maritime sector evolution in the last decades and years (UNCTAD, 2017a; UNCTAD2017b), as well as on reports projecting the future scenarios in 2030 (Lloyds

Register, 2013). The analysed reports and data suggest that the average capacity / dimensions (DWT) of the ships is the parameter that will increase most in the upcoming years and decades, and we also consider that this is arguably the most relevant parameter in terms of environmental risks.

V.4.2.5 Metocean conditions

The risk model makes use of metocean conditions a) for the definition of correction factors related to the probability of having an accident, and b) as forcing conditions for the fate and behaviour of the oil spill simulations, which is used to estimate the severity related to the hypothetical vessel-based spilled oil amount reaching shoreline, as explained in section V.4.2.2 (in the part related with Amount of contaminant reaching ashore).

The used metocean conditions are based in operational modelling systems that cover the whole Portuguese continental coast. Currents and water properties (sea surface temperature, sea surface salinity) are obtained from hourly outputs of PCOMS-MOHID model (Mateus et al., 2012, Pinto et al., 2012). PCOMS is a 3-D hydro-biogeochemical model of the Iberian Western Atlantic region. Ocean boundary conditions are provided by the Mercator-Ocean PSY2V4 North Atlantic and by tidal levels computed by a 2-D version of MOHID (Neves, 2013; Ascione Kenov et al., 2014), forced by FES2004, and running on a wider region. PCOMS has a horizontal resolution of 6.6 km and a vertical discretization of 50 layers with increasing resolution from the sea bottom upward, reaching 1 m at the surface (Ascione Kenov et al., 2014).

Atmospheric conditions (wind velocity, surface air temperature, atmospheric pressure and visibility) are obtained from the meteorological forecasting system IST-MM5, using MM5 model (Grell et al.1994) with a 9km spatial resolution. This operational model was initially implemented by Sousa, 2002, and updated in 2005 (Trancoso, 2012). This model is also used as atmospheric forcing of PCOMS-MOHID, and its outputs are also every hour.

The wave parameters (wave period, wave height, wave direction and wave length) are obtained from the Portuguese wave forecasting system implemented at MARETEC-IST, using WaveWatchIII model (version 3.14 – Tolman, 2009) with a 5km spatial resolution, and wind forcing provided by Global Forecasting System (GFS) from the National Oceanic and Atmospheric Administration (NOAA), with a spatial resolution of 0.5° (Franz et al., 2014).

The reference metocean conditions selected for the risk characterization in the area of study correspond to the full year of 2013. In order to allow to understand the degree of representativeness of the year of 2013 in relation to the climatology, comparisons between the metocean model results for year of 2013 vs. 5-year set (2011-2016) were performed. Three different points distributed along the Portuguese continental coast were selected for comparison. The selected points are located in the vessel traffic corridors, as can be seen in Figure 72.

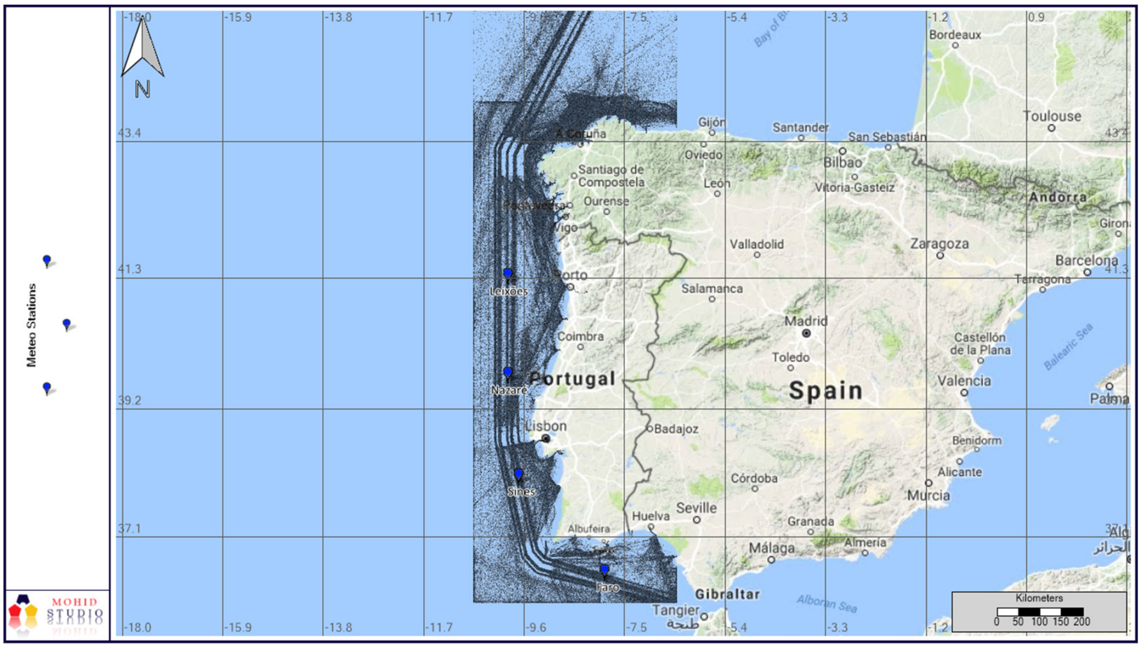
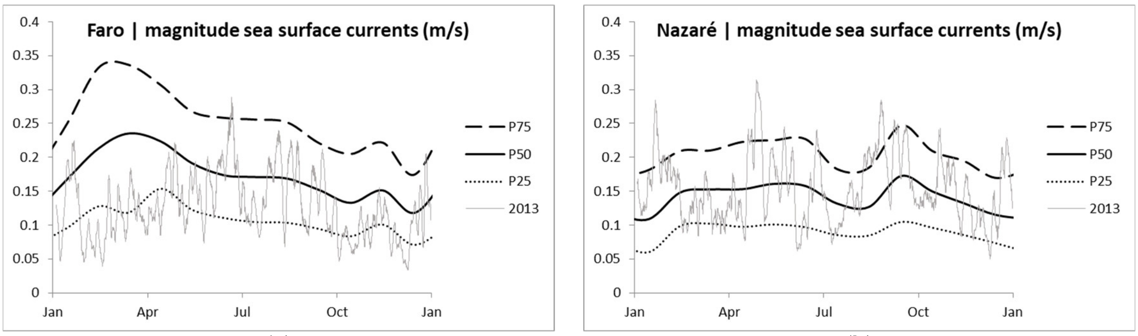


Figure 72 - Vessel positions in 2013 (source: MarineTraffic), and virtual stations selected for metocean comparison

Average monthly statistical data (percentiles) were obtained for the 5-year period, and compared with the modelling results (3-day moving averages) obtained for 2013 (Annex 3). Results have shown that globally, in 2013, the metocean conditions are in agreement with the monthly tendencies – which indicates that generally speaking, 2013 reflects a typical year. The only atypical situations are:

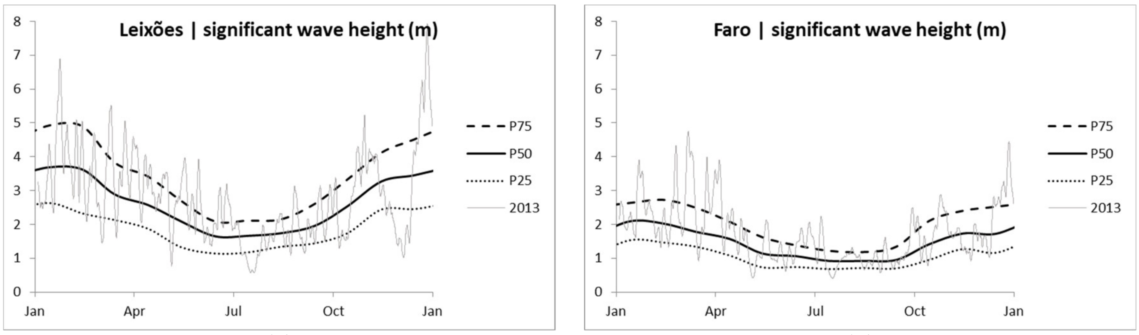
- the lower sea surface currents in Faro, during the first 4 months of the year (with values consistently below the percentile25). However, it seems to be a localized situation, having in mind that we have also analysed the results in points more located in the Center or in the North (e.g. Nazaré) of Portugal, and in these cases, comparisons indicate that the currents in 2013 are in line with the typical situations.



(a) (b)

Figure 73 – Comparisons between sea surface current conditions (magnitude) in the periods 2011-2016 vs. 2013, for locations close to Faro (a) and Nazaré (b)

- The wave conditions at the end of 2013 (in all the analysed points, except Faro): values seem to be consistently lower than normal in the beginning of December, and greater than normal in the end of the year (although maritime storms can be frequent during the winter season).



(a) (b)

Figure 74 - Comparisons between wave conditions in the periods 2011-2016 vs. 2013, for locations close to Leixões (a) and Faro (b).

For the estimation of risk in the long-term scenario related with climate change, it was assumed a generic 4% reduction of the significant wave height, based on the conclusions in Ribeiro et al., 2013. This study refers this wave parameter as the most significant in terms of modification related to climate change phenomenon.

V.4.3 Results

The results were organized according to the risk approach analysed: vessel accident risks and shoreline contamination risks.

V.4.3.1 Vessel accident risk

The first part of the results was focussed on the characterization of the reference situation (2013), and then future projected scenarios were also described.

Hindcast analysis (reference year: 2013)

The vessel accident risks were integrated in different seasons, and results were mapped and statistically processed. The risk values were also normalized following a max-min approach, between 0 (yearly minimum) and 1 (yearly maximum), in order to facilitate the analysis.

The Table 19 shows the statistical parameters obtained from the integrated vessel accident risks in the area of study, during the whole year of 2013, as well as for the Summer (April – September) and Winter (January-March + October-December) months of 2013. The results are presented in absolute and normalized values.

Table 19 – Statistical parameters for vessel accident risks (normalized) in the Portuguese coast during 2013.

	Absolute values			Normalized values		
Parameter	Year	Summer	Winter	Year	Summer	Winter
Minimum	4.63	4.63	4.63	0	0	0
Average	8.53	8.49	8.57	0.57	0.56	0.58
Maximum	11.47	11.47	11.35	1	1	0.98
Std. deviation	0.77	0.77	0.77	0.11	0.11	0.11
Percentile25	8.25	8.23	8.29	0.53	0.53	0.54
Percentile50	8.49	8.41	8.58	0.56	0.55	0.58
Percentile75	8.77	8.72	8.80	0.61	0.60	0.61

In the previous table, the differences between the integrated vessel accident risks in summer and winter can be observed in the percentiles and in the averages – with higher values in winter, as expected. Nevertheless, the maximum risk value was registered during summer. Both seasons have the same minimum risk value and standard deviation.

The next images (Figure 75 and Figure 76) map the integrated vessel accident risks in the area of study, during the whole year of 2013, as well as for the Summer (April – September) and Winter (January-March + October-December) months of 2013.

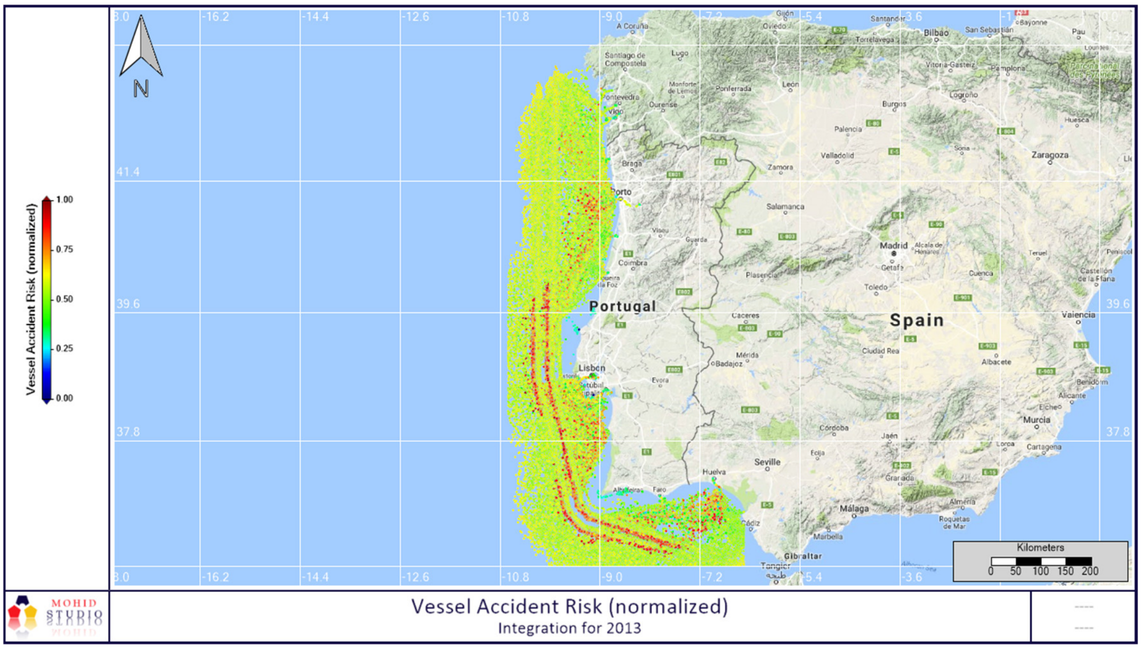


Figure 75 – Map visualization of the vessel accident risks (normalized) along the whole year of 2013

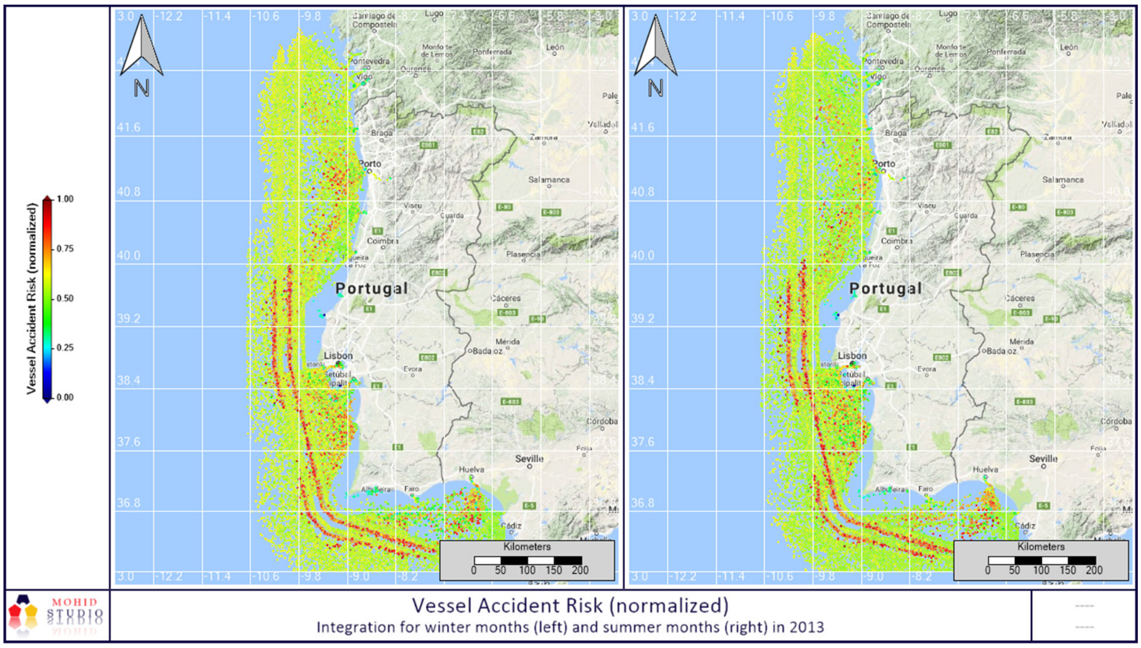


Figure 76 - Map visualization of the vessel accident risks (normalized) grouped in winter (left) and summer (right) months during 2013.

After analysing the vessel accident risk map integrated for the whole year of 2013 (Figure 75), the following aspects can be noted:

- The highest risk values are estimated in the vessel traffic corridors, and mostly in the Center and South of Portugal.
- Some coastal regions are much less exposed to vessel accident risks, because the vessel traffic in those zones is very low (this aspect could be inferred immediately

after observing Figure 72). Some examples of these areas can be found between Cascais and Figueira da Foz; or between Sines and Sagres. In the other hand the Northern coast is clearly more exposed to vessel accident risks, although some high risks can be found in sensitive coastal areas in South, including Lisbon, Sado and Faro estuaries.

If we compare the risks estimated in different weather seasons (Figure 76), in a general way and at first sight, no significant differences can be noted in risk patterns, which means probably that in the risk model implemented, the metocean conditions are less important than other aspects (e.g. vessel type; vessel size). Nevertheless, after observing with more detail, some higher values can be found during winter season. The major differences in risk patterns can be found in the North of Portugal:

- close to Porto (latitude 41; longitude -9.4), the risk is visibly higher during winter;
- values tend to be generally a bit higher above 39.2º latitude (probably related with more variations in metocean conditions; e.g. wave height is higher in the Center and North of Portugal)

An interesting analysis that can also be made is a visual comparison between the vessel accident risk maps shown above, and the oil spill hazard mapping as a result from oil spill simulations from slicks detected by CleanSeaNet (Fernandes et al., 2017a). The next image (Figure 77) presents the cumulative concentrations (kg/m^2) in the Portuguese continental coast as a result from oil spill simulations from slicks detected by CleanSeaNet between 1-9-2011 and 1-9-2016 (image from Fernandes et al., 2017a).

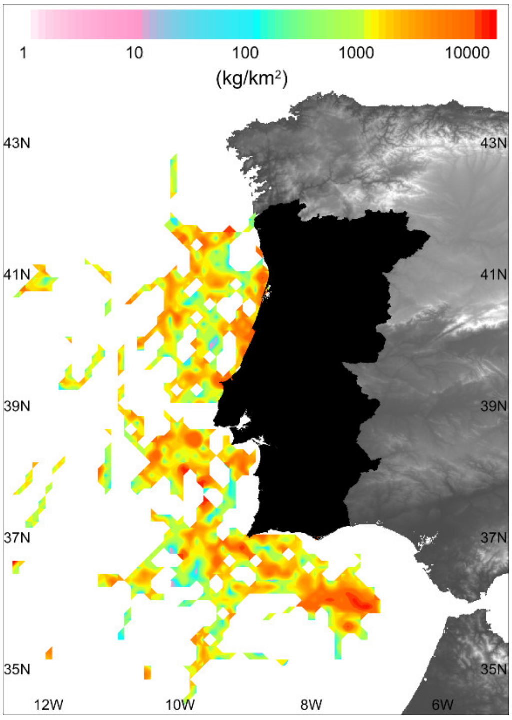


Figure 77 - Cumulative oil concentrations (kg/km2) in the Portuguese continental coast as a result from oil spill simulations from slicks detected by CleanSeaNet between 1-9-2011 and 1-9-2016. Source: Fernandes et al., 2017a

The previous figure and Figure 75 have similarities, which allows to confirm that most of the detected oil slicks can be indeed associated to high vessel traffic areas crossed by vessels with bigger dimensions and / or by vessels that present more risk of oil spills (e.g. tankers). Those are the main factors that control the risk model here presented.

Future projected scenarios

Based on the long-term (20-30 years) projected future scenarios detailed in the methodology (chapter 2.3), two different approaches were considered for the risk model: a) evolution in maritime transport - increase vessel sizes; b) climate change scenarios – overall decrease of significant wave height.

In the case of the maritime transport projected scenario, the DWT values from the vessel AIS data were increased in 100% (i.e., the double) for all the vessels, and all the other parameters and configurations were kept equal to the 2013 hindcast scenario.

In the case of the climate change projected scenario, the significant wave height values were decreased by 4%, and all the other parameters and configurations were kept equal to the 2013 hindcast scenario.

The results obtained from these two scenarios were compiled and statistically analysed, in comparison with the reference scenario for 2013. These results are presented in the following Table 20.

Table 20 – Statistical analysis for vessel accident risks in reference scenario and future projected scenarios

Parameter	Reference hindcast scenario (2013)	Maritime transport scenario (increase DWT)	Climate change projected scenario (lower sign. wave height)
Minimum	4.63	4.63 (0%)	4.63 (0%)
Average	8.53	8.62 (+1.1%)	8.41 (-1.4%)
Maximum	11.47	12.02 (+4.8%)	11.32 (-1.3%)
Std. deviation	0.77	0.86 (+11.7%)	0.76 (-1.3%)
Percentile25	8.25	8.28 (+0.4%)	8.21 (-0.5%)
Percentile50	8.49	8.56 (+0.8%)	8.35 (-1.6%)
Percentile75	8.77	8.83 (+0.7%)	8.53 (-2.7%)
Percentile95	10.15	10.48 (+3.2%)	10.12 (-0.3%)

The scenario related with the evolution of maritime transport shows visible increase in terms of maximum risk values (+4.8%) and percentile95 (+3.2%), while the minimum values keep the same. As a result, the standard deviation increases significantly (+11.7%). The average and median (percentile50) values only present a slight increase (around 1%).

In the other hand, the second projected scenario (climate change projected scenario, i.e., decreasing significant wave height), gives a generic reduction of risk values with an average reduction of 1.4%.

V.4.3.2 Shoreline contamination risks

Although vessel accident risk provides a methodology for mapping the risk of spill, it doesn't allow to conclude or to estimate if the coastline is indeed potentially impacted as a consequence of vessel accidents. This analysis is made with the application of the shoreline contamination risk mapping.

As in the vessel accident risk analysis, the first part of the results related to the shoreline contamination risk is focussed on the characterization of the reference situation (2013), and then future projected scenarios are also described.

Hindcast analysis (reference year: 2013)

Instant risk values (one output every 6 hours) were obtained per shoreline segment. 1045 shoreline segments are included, and thus, for each year, more than 1.5 million risk values are obtained. In order to facilitate the results analysis, risk values were integrated along time and space, and generic statistical procedures were applied.

As already mentioned, during the risk characterization process, two different shoreline methods were applied on the estimation of severity / amount of oil reaching shoreline: one considering the distance between vessel and the shoreline (non-modelled shoreline contamination risk) and the other one using the oil spill model to compute the amount of oil reaching to the nearshore (modelled shoreline contamination risk), assuming virtual spills based on the vessels movement. With an average number of 250 vessels crossing the Portuguese coastline in each time instant, a total approximate number of 365 000 oil spill simulations was processed along the year of 2013.

- **Global overview**

A global statistical overview of the absolute shoreline risk values can be found in the following table (Table 21). (Total values are only based in the whole set of instant risk values. Mean parameters are obtained over space - as an example, the mean minimum is the spatially-averaged minimum. i.e., first: we found the minimum for each shoreline segment, along the year; second: we found the average for all the minimums obtained for all the segments.)

Table 21 - Statistical analysis for non-modelled and modelled shoreline contamination risks in reference scenario (2013)

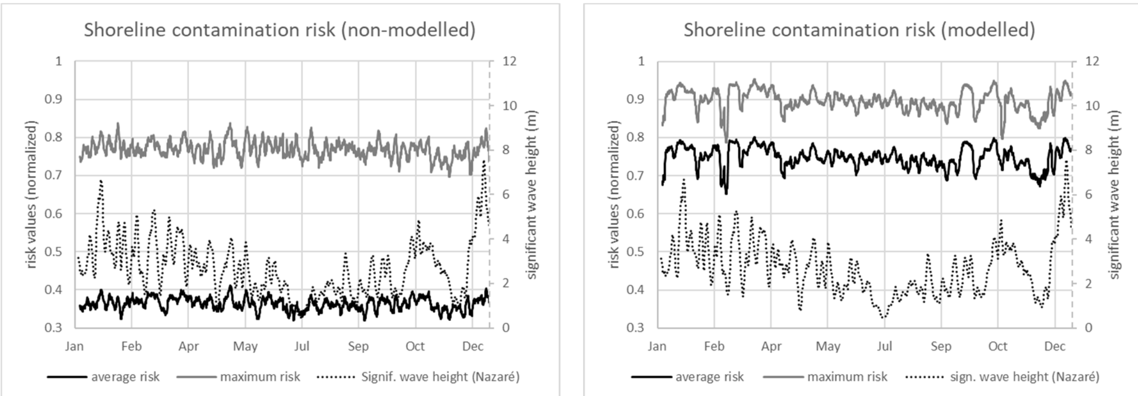
Statistical parameter	Non-modelled	Modelled
Total average	7.70	8.90
Total minimum	6.00	0.19
Total maximum	10.67	11.83
Total standard deviation	0.75	0.82
Total percentile25	7.18	8.39
Total percentile50	7.76	8.93
Total percentile75	8.23	9.46
Mean average	7.66	8.90
Mean minimum	6.36	4.12
Mean maximum	8.92	10.04
Mean standard deviation	0.42	0.58
Mean percentile25	7.36	8.67
Mean percentile50	7.68	8.98
Mean percentile75	7.96	9.26

The results obtained with the modelled approach generate higher risk values for most of the parameters, except the minimum values, which are much lower in the modelled simulations. These low values are specifically obtained when the metocean conditions are favourable to transport oil to the open ocean and far away from the coast. As a result, variability (standard deviation) is also higher in the modelled approach.

- **Spatial integration: variation along time**

Since the adopted risk value is dynamic, the shoreline risk values vary along time as a function of the different vessels and metocean conditions.

Figure 78 shows the time evolution of the spatially-integrated (over the whole coast) risk evolution (modelled and non-modelled results), based in normalized risk values, between 0 (minimum risk value) and 1 (maximum risk value). We compare the spatially-integrated risk levels with instant significant wave height in the point of Nazaré (exact location shown in Figure 72). All the variables in the graphic are presented in 3-day moving averages.



(a) (b)

Figure 78 - Spatially-integrated risk evolution (non-modelled – (a) and modelled – (b) results) along the year of 2013 and comparison with estimated significant wave height in Nazaré virtual station. Results presented in 3-day moving averages.

The previous figure shows that the modelled risk approach (b) is much more responsive to variations with the metocean conditions (in the figure represented with the significant wave height). In the modelled risk approach, it is clearly visible that high values of risk and higher variability are more frequent in winter. In the non-modelled approach, although metocean conditions influence the probability of accidents, the obtained shoreline risk values don't seem to reflect seasonal variations so clearly.

- **Time integration: variation along coast**

Here we include a statistical analysis of the timely integrated risk levels in the different shoreline segments considered in the area of study. The results were normalized between 0 and 1, mapped[3] for ranking shoreline segments in respect to different statistical parameters (Figure 79 and Figure 80), and in the different risk approaches: modelled and non-modelled. A high non-modelled risk value in a shoreline segment means the combined existence of several vessels in the vicinity of a highly sensitive coastal area. A high modelled risk value in a shoreline segment means the combined existence of several vessels that may potentially release oil with expected contamination near that shoreline segment, which also has to be highly sensitive.

One aspect to be noted is the fact that, for each risk approach, the obtained ranking in relation to the shoreline segments presenting highest maximum risk values has a ranking similar to the segments with highest percentile50 (or median) and average risk values. Therefore, to avoid redundancy in the results here presented, only two types of maps are included in the figures: "hot spots" (segments with highest maximum / median / average risk values), and "cold spots" (segments with minimum risk values).

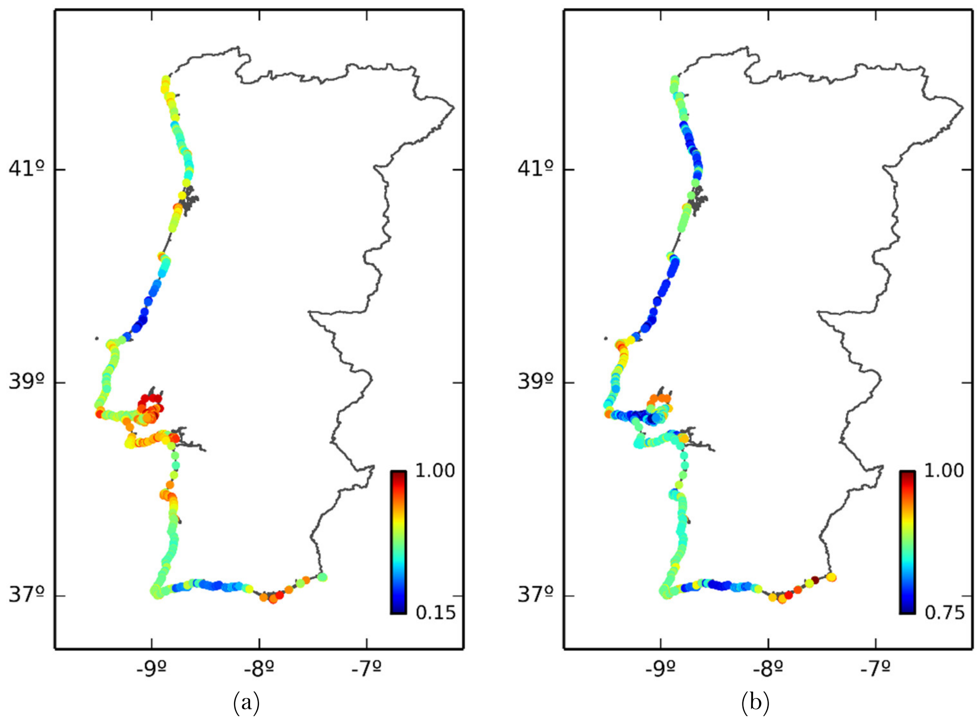


Figure 79 - "Hot spots" obtained for the different risk modelling approaches during the year of 2013: a) non-modelled; b) modelled.

[3] The shoreline segments are visually represented in the maps by points (and not by lines), located in the beginning of each shoreline segment. Since some shoreline segments have higher length (due to less spatial variability in coastal sensitivity), as a result, those coastal zones may look in the maps without any point. However, in the risk algorithm, those areas were indeed covered by shoreline segments.

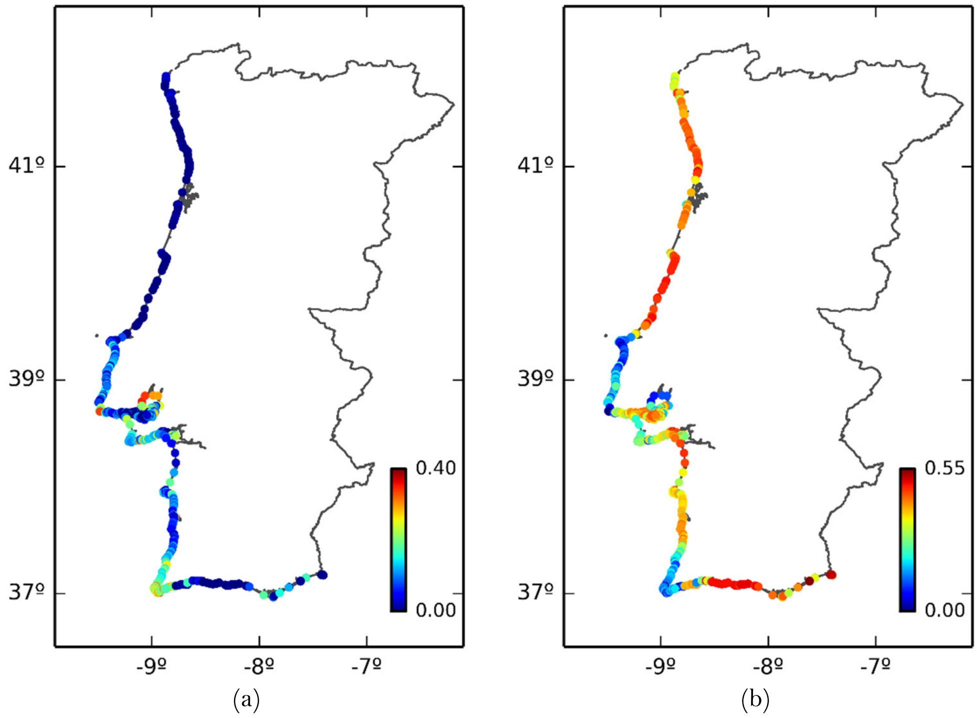


Figure 80 - "Cold spots" obtained for the different risk modelling approaches during the year of 2013: a) non-modelled; b) modelled.

The first aspect to be noted in the previous maps (Figure 79 and Figure 80) is the difference between non-modelled (no oil spill model; severity based in distance between vessels and shoreline) and modelled approach, in terms of ranking related with the shoreline segments.

In relation to the hot spots (Figure 79), from a non-modelled approach (a), Tagus and Sado estuary, as well as Faro (all of them areas with high coastal sensitivity), are the areas with higher risk of shoreline contamination. This means that these are the highly sensitive areas with more vessels in the proximity. However, if we take in consideration the oil spill model (b), the areas at higher risk change considerably, and the southeast coast of Portugal (Tavira, Olhão, Cacela) – a region particularly sensitive as well - is more vulnerable to oil contamination than the other regions. This is not in agreement with recent research studies, that instead of the eastern coast, identified the western municipalities of Algarve as the most impacted by oil spills – for instance, Neves et al., 2013. However, it should be noted that this referred work is focussed in the development of a novel methodology, rather than providing a realistic oil spill risk in Algarve (as the authors refer), due to some technical limitations, including the low oil spill model spatial resolution (1/4-degree resolution, i.e., 7 grid cells for the whole coast of Algarve), and static vessel traffic data obtained for only one month.

Localized sites in Peniche, Cascais and the inner Tagus estuary also have some relevant hot spots. Another interesting aspect is the difference in relation to the North of Portugal: while the non-modelled risk approach estimates relatively high risk in that region, the modelled risk approach estimates low risk of contamination in the same coastal areas. This must be linked to the metocean conditions and the associated transport of potentially spilled oil, that may be favourable to somehow transport the oil away from those areas and thus reduce the risk of shoreline contamination.

As regard to the cold spots (the shoreline segments that registered the lowest risk values in 2013), once again, significant differences are found between the risk approaches. The non-modelled approach ranks some areas at the Center of Algarve (south coast) and in the Center (west coast) and North of Portugal as the areas with estimated lowest risk values. To achieve these results, a combination of low sensitivity indices and temporary inexistence of vessels in the vicinity is needed. In relation to the modelled approach, the "cold spots" were found between Cabo Raso (38.7º latitude) and Peniche (39.5º latitude), as well as in southwest coast, in the vicinity of Sagres (-9º longitude, 37º latitude). This is only justified by sporadic favourable metocean conditions, having in mind that those areas are also crossed by busy international marine traffic corridors.

An additional aspect to be noted from the previous maps is the high variability in terms of modelled risk values obtained inside the Tagus estuary (this zone has high risk values, but some of the lowest values were also recorded there). This can be seen as a realistic estimation, because in fact the estuary is a highly dynamic environment.

The shoreline contamination risk levels can also be integrated in different annual seasons: summer months and winter months, as it was performed in the vessel accident risk analysis (chapter V.4.3.1). Following this methodology, the risk ranking obtained for the modelled shoreline segments in relation to maximum risk (hot spots) and minimum risk levels (cold spots), duly grouped according the corresponding weather season, is also analysed.

Although the maps for maximum values tend to be quite similar in winter and summer, the segments with lowest risk present significant change according to the season, as can be seen in Figure 81.

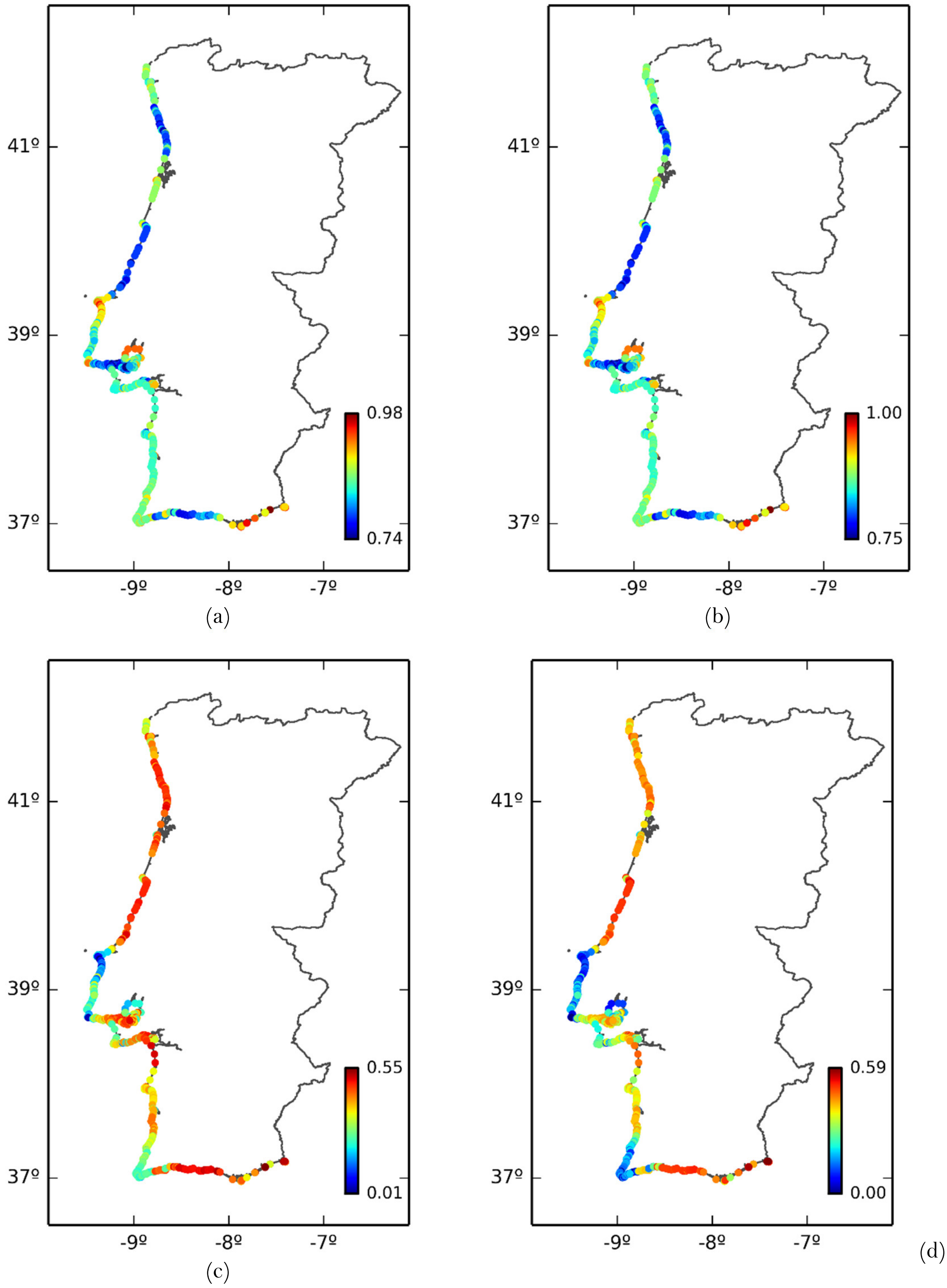


Figure 81 - “Hot spots” and “cold spots” obtained for the modelling risk approach, and grouped according to the weather seasons during the year of 2013: a) “hot spots” in summer months; b) “hot spots” in winter months; c) “cold spots” in summer months; d) “cold spots” in winter months.

In the previous figure, the lowest risk values in Summer months were identified in the western coast between Cabo Raso and Peniche; in Winter months, this same region is also a “cold spot”, as well as the southwestern region, close to Sagres.

Future projected scenarios

Using the same modelling scenarios detailed in V.4.3.1 - Future projected scenarios, it is possible to evaluate how different would be the impacts in the shoreline in those projected scenarios, when compared with the reference situation of 2013. Namely: what will be the risk modification in case of the expected growth in vessel dimensions? Are there any changes in the most and least affected shoreline segments? And in case of projected climatic changes (which would mean an overall decrease in significant wave height)?

Only comparisons with the modelled scenarios are included in this section, since it is assumed as the most realistic and complete approach.

- **Global overview**

In the next table, we present the statistical parameters obtained for modelled shoreline contamination risk, comparing the values obtained for 2013 and the projected scenarios.

Table 22 – statistical parameters obtained for the modelled shoreline risk contamination in 2013, in the reference scenario and in future projected scenarios.

Statistical parameter	Reference hindcast scenario (2013)	Maritime transport scenario (increase DWT)	Climate change projected scenario (lower sign. wave height)
Total average	8.90	8.96 (+0.7%)	8.89 (-0.1%)
Total maximum	11.83	11.94 (+0.9%)	11.90 (-0.6%)
Total standard deviation	0.82	0.83 (1.2%)	0.82 (0%)
Total percentile25	8.39	8.44 (+0.6%)	8.38 (-0.1%)
Total percentile50	8.93	8.99 (+0.7%)	8.93 (0%)
Total percentile75	9.46	9.52 (+0.6%)	9.45 (-0.1%)

According to the risk model used, the global rate of increase or decrease in terms of risk levels are not significant in any of the statistical parameters obtained for both studied scenarios. As expected, the increase of tonnage also increases the statistical parameters for the risk values, and the reduction of significant wave height reduces the statistical parameters for the corresponding risk values.

- **Time integration: variation along the coast**

The different configurations (different vessel tonnage; different significant wave height) used in the projected scenarios may generate geographical changes in the modelled shoreline risk levels and risk distribution in the Portuguese coastline, in terms of the main risk "hot spots", or the areas with lowest risk. In the next two figures (Figure 82 -

Figure 83), we present the risk ranking maps for the future projected scenarios in terms of hot spots and cold spots, using the modelled approach. The risk values are normalized between the minimum and maximum values from the modelled shoreline risk values obtained for the reference scenario (2013) (which means that values above 1 are possible, in all the locations where risk in projected scenarios are greater than the maximum risk in reference scenario).

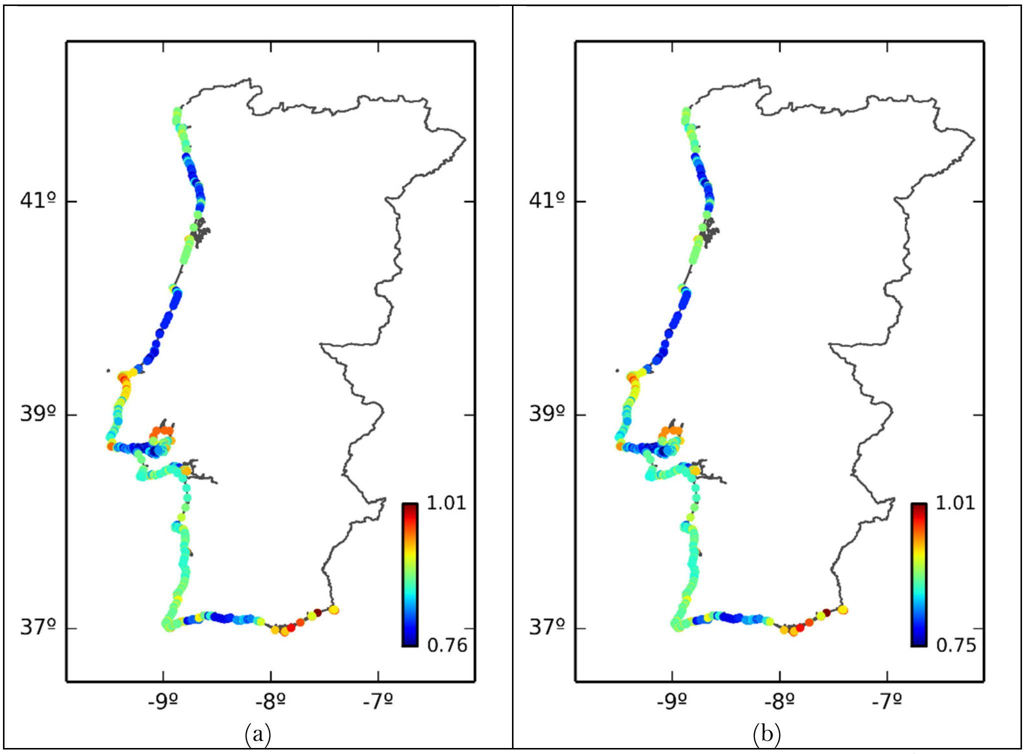


Figure 82 - "Hot spots" obtained for the modelling approach and in the different future projected scenarios studied. Maritime transport scenario (increase of DWT): (a); climate change scenario (decrease on significant wave height): (b).

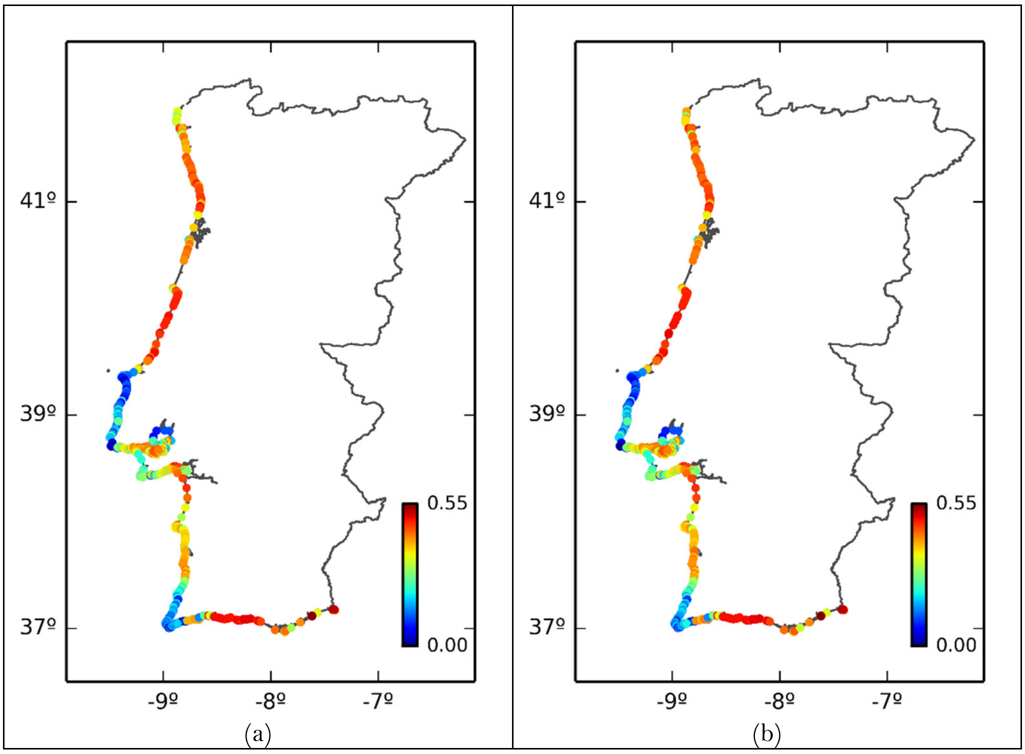


Figure 83 - "Cold spots" obtained for the modelling approach and in the different future projected scenarios studied. Maritime transport scenario (increase of DWT): (a); climate change scenario (decrease on significant wave height): (b).

From the previous figures, and when compared with the modelled reference scenario (Figure 79b) and Figure 80b)), they present a similar distribution. In relation to the hot spots, and particularly in the maritime transport scenario, the main difference is found in the west coast, in Peniche and Lourinhã (between latitude 39º and 39.4º) – the maximum values here tend to increase more than in other regions. This is not independent of the fact that this region is in the vicinity of important international marine traffic corridors, crossed by some of the vessels with higher dimensions - and at higher risk, as can be seen in Figure 75.

In relation to the shoreline segments with minimum contamination risks, the main differences are visible in the North of Portugal in Viana do Castelo – Caminha (latitude 41.6º – 42º): the decrease of significant wave height associated to climatic changes will not contribute to reduce the shoreline contamination in this area – in fact is the opposite: the risks will increase in this zone. Possibly due to a slight modification of the transport or behaviour of oil spills due to waves (e.g. Stokes drift) that might not be favourable to this region.

V.4.4 Discussion and conclusions

The study here presented allowed to characterize the risk profile and evolution in the Portuguese continental coast in terms of exposure and vulnerability to oil spills from vessels. Based in a dynamic and holistic risk approach that combines variable vessel traffic, statistical data from previous accidents, metocean modelled conditions, high resolution coastal sensitivity and oil spill modelling, the risk methodology revealed to be versatile enough to be applied not only in real-time as a monitoring decision support tool (in the scope of a previous work from Fernandes, 2016), but also as a valuable instrument for improvement of contingency planning and strategic decisions, having in mind that the system can be used to characterize a typical year, or to study the evolution in the upcoming years. This was indeed the main purpose of this work.

The comparison of different risk approaches (vessel accident risk; non-modelled, and modelled shoreline risk), different seasons and also different scenarios (reference scenario and projected future scenarios) allowed to obtain complementary information about the risk behaviour, to identify seasonal and regional patterns, and to test the sensitivity of the model to different conditions and configurations.

Moreover, the extensive and comprehensive results obtained for one complete year (2013) allowed to better calibrate and classify the risk scale and risk patterns. Several results were generated in the scope of this work, for each one of the 1045 shoreline segments. However, only a small part was here presented. Although the application of the risk model in one complete year has been already a technical challenge, the validity of the results would certainly increase if a longer period (e.g. 5 years) was analysed. Nevertheless, the selected period was considered as a valid representation of the typical conditions (vessel traffic and metocean data) in the area of study.

From a general point of view, the results showed that the vessel accident risks are greater in the Center and North of Portugal – in the international vessel marine corridors, and in line with the information related with EMSA's CLEANSEANET (remotely detected oil spills) for the Portuguese coast.

In terms of shoreline contamination risks, it was shown the influence of integrating an oil spill model as part of the risk algorithm. The obtained results with and without oil spill modelling show significant differences in the risk maps. The most relevant notes on the risk analysis are the high risk of shoreline contamination identified in the south-eastern Portuguese coast (Tavira, Olhão, Cacela), as well as in other localized areas like

Peniche, inner Tagus estuary and Cascais. The analysis also allowed the identification of the lowest risks in some areas that are usually classified as areas of great risk – for instance, the region of Sagres (at least in Winter months), in the western Algarve.

The application of the risk study to future projected scenarios allowed to conclude that with the presented risk model, the increase of vessel dimensions (which has been identified as a major trend in the next years), or the decrease of significant wave height as an identified consequence of climate change effects, don't represent important risk modifications in terms of maximum and minimum values on the risk of shoreline contamination. Eventually, the combination of other parameters (e.g. increasing vessel traffic; inclusion of extreme scenarios) would provide increased risks. The risk model could also be modified in order to be more sensitive to some of these parameters, by increasing their relative weight in the probability and / or in the consequences.

In terms of spatial resolution, the risk model uses metocean conditions and oil spill computational mesh that cover the whole Portuguese continental coast (approx. 6km except meteorological model outputs, that have 9km resolution), but the spatial discretization included is not in the same spatial level as the coastal sensitivity, which has higher resolution (the average length of the shoreline segments is 1230m). Nevertheless, the inclusion of coastal sensitivity indices with a good spatial resolution is rather important to avoid losing more information in the risk computation procedure. In the future, higher resolution metocean and oil spill models can also be included in the process, in order to perform local risk characterization.

In relation to time resolution, the validity of results would possibly increase if outputs were generated every hour. However, the existing data related to vessel traffic (AIS) only covers outputs every 3 hours. In the course of this study, several tests were made with 3-hour outputs vs. 6-hour output time step, but no significant differences were identified.

The risk methodology here applied can also be adapted to monitor or to assess multiple other environmental topics: offshore oil platforms; dispersion of ballast water discharges and risk of spreading alien invasive species; water quality in bathing waters; atmospheric pollution from vessels; marine litter.

V.4.5 Acknowledgements

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VI Concluding remarks and considerations for future research

VI.1.1 Acknowledgements

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VI.2 Major contributions

The study aimed at contributing to the potential reduction of coastal environmental impacts related to oil spills from vessels, by developing and applying a model-based integrated risk management framework capable of supporting decision-makers in planning, prevention, preparedness, response and damage assessment strategies.

The development of the strategy was built in the assumption that numerical modelling can play an important role in this process – specifically, the proposed solution was an operational software infrastructure composed of complementary decision support systems capable of helping decision makers in the multiple stages or risk management, and supported by existing metocean models and essentially, by an efficient, reliable, flexible and state-of-the art oil spill fate & behaviour numerical model.

The model was reformulated to respond to the operational challenges posed in this thesis. It was also calibrated, tested and verified for some of the processes, with exercises with drifting buoys and / or real accidents, as far as possible. Still, some of the processes developed were not duly validated in the course of the thesis, whose difficulty was mainly related to the few data available in the study area.

The metocean models used for the study area (used in the calculation of the risk and as forcing of the drift model) are duly validated with in-situ data and remote sensing (although those activities are out of the scope of the work plan of this thesis).

In order to enhance tactical and operational capacity for decision makers in regard to oil spill preparedness and response, a new type of decision support systems was designed – an operational system for on-demand prediction of fate and behaviour of oil spills. The designed system should be able to be simultaneously user-friendly, fast, transferable and reliable in terms of the quality of the results presented. This could only be achieved by connecting the developed oil spill model (and the lagrangian component) with metocean forecasting systems, and using an efficient coding, in order to accelerate the computational process. The designed system was integrated in multiple operational distinct platforms (Aquasafe, MOHID Studio, and more recently in ACTION Seaport – Fernandes et al., 2017b). The performance was analysed and compared to similar platforms applied in other areas of application. The designed tool has proven to be able to generate results in less than 2 minutes, allowing the incorporation of different multiple metocean modelling systems for different spatial scales. After operational implementations in different areas in the world during the course of this thesis (e.g. Porto de Leixões, Tuscany, Malacca Strait, Porto de Lisboa), the obtained achievements are in line with the objectives proposed. Furthermore, as demonstrated in the thesis, the designed on-demand systems are still evolving to extend to other regions, and including additional technological developments (e.g. ACTION Seaport web-based platform), processes and models (e.g. chemical spill modelling) – while keeping the same concept and the same modelling platform (MOHID lagrangian component). The illustrated example of this on-going work is the application in the area concerning Canary Islands-Madeira-Morocco (MARPOCS project).

Similarly, another type of decision support tool was designed to answer the needs and challenges raised in the thesis work: the possibility of adopting the developed oil spill model in an automated system for near-real time prediction of oil spills from EU satellite-based detection service. Taking advantage of EMSA's CLEANSEANET oil spill (remote sensing) detection operational service, and from the flexibility and efficiency of MOHID oil spill model, a human-independent operational system was built to provide email notifications to marine pollution authorities, with details regarding the expected forecast for a CLEANSEANET-detected oil spill, and also to provide a retrospective of the detected slick (backtracking modelling), helping the authorities in the identification of potential polluters involved in the incident. With the operational notifications sent in less than 5-15 minutes after CLEANSEANET report, the decision support system is considered to represent a fast first-guess forecast solution to maritime authorities, allowing them to improve anticipation of tactical response, to be more effective on the identification of the pollution source, and to have more time available for running detailed on-demand forecasts.

The coupling of CLEANSEANET and MOHID oil spill system also provided the opportunity to build a hazard assessment in the Portuguese continental coast, based on the integrated analysis of drift model simulations from previously detected spills using metocean model data. Although without specific tactical benefit, the generated hazard assessment is a valuable instrument for the development of efficient planning and prevention strategies.

The ultimate stage of the thesis was the development of a holistic approach for the quantification of shoreline contamination risk from vessel-based oil spills. The challenge was to dynamically estimate the shoreline risk levels from vessel-based oil spills, analysing the relative weight of the different factors that actively contribute to influence those risk levels. Among those factors, one has considered the vessel data obtained from AIS, statistical data from past incidents and their relation with ship types, coastal sensitivity, metocean conditions (from operational models), and the amount of oil reaching coastal areas as a result of potential spills continuously simulated from those vessels.

The coastal sensitivity (sensitivity indices) was obtained for the area of study, using, adapting and improving previously developed methodologies. The developed methodology has also been applied by other institutions in other regions of Portugal (e.g. application to Madeira island by ARDITI-OOM, in the scope of MARPOCS project). The same operational modelling systems previously used were also integrated in the system. The amount of potential oil reaching the coastline was simulated benefiting from the developed oil spill model, duly coupled to the metocean operational models.

The risk model methodology was implemented in MOHID Studio, and its relevance was tested and demonstrated through sensitivity analysis to different metocean conditions and to use vs. not use the oil spill model in the risk approach. Having a risk model approach dynamically sensitive to metocean conditions in space and time, results are more realistic.

The possibility of using this decision support system in real-time provides the ability to establish intelligent monitoring, resource optimization and maritime awareness in relation to the dynamic evolution of the coastal risk.

The previously mentioned holistic risk tool can also be used for historical analysis or scenario-based assessment. Having the Portuguese continental coast as the target area, a comprehensive risk assessment for the Portuguese coast was conducted, not only under realistic past-recent oceanographic and ship traffic conditions, but also assuming climate change scenarios and future trends in global shipping. The application of the risk approach in Portuguese continental coast in the complete year of 2013 allowed to identify south-eastern coast of Portugal as one of the critical "hot spots" in terms of shoreline contamination risk, instead of the western coast of Algarve (e.g. Sagres), which in fact was identified as a location with the lowest contamination risk levels during winter months. Other localized points in Peniche or in the vicinity of Cascais were also classified as high-risk sites.

After identifying the main local hotspots, seasonal behaviour, and potential evolution of risk in the future, the obtained risk assessment provides a relevant instrument for strategic planning and development of prevention mechanisms. Thus, the developed decision support tool for holistic risk modelling answers the main questions raised in the course of the thesis.

As a final remark, the developed strategy, and the results accomplished with this study showed its usefulness and applicability of advanced numerical modelling as supporting tools for improving decision makers in the management of oil spill events at sea, in the multiple stages that are involved in emergency and risk management.

Nevertheless, some limitations were identified and questions have arisen across the study. Future research and development in these aspects are discussed in the next section.

VI.3 Considerations for future research

Future research should account for the inclusion of new processes in oil spill model, in order to increase its applicability in terms of estimation of quantification of environmental consequences and biological impacts. The model should be prepared for estimation of the biological effects in the marine biota, determining injuries (acute toxicities), lost production in the future (population modelling), or even chronic effects that can be bio-amplified.

This modelling capacity would represent a significant advance for the definition of monitoring protocols in oil spills, but also on a better definition of claims and compensation in the case of oil spills. Ultimately, this modelling capacity can be used in a NEBA (Network Environmental Benefit Analysis) approach, together with the modelling of clean-up and response operations. This approach provides a good instrument in contingency planning, anticipating and facilitating the decision in terms of application of response and clean-up measures.

More validation should be conducted with the oil spill model, and particularly in relation to the new implemented capacities. This validation should be performed using different strategies: a) under controlled environmental conditions (laboratory), b) using real data from past incidents and exercises, c) model intercomparison. In the case of lab experiments, the main problem is the access to existing data (most of the available data is protected, being proprietary from oil companies). In relation to real-data, it is extremely difficult to measure all the processes and environmental conditions, in order to implement an effective validation. Comparing oil spill model results with drifting buoys is simply not enough, as most of the drifting buoys will behave differently when compared to an oil spill. Simple model intercomparison might be a good approach, but in theory, if all models represent a process in the same way, it can mean that all models are equally correct, or incorrect. Nevertheless, intercomparison is also cost-efficient when compared with other methodologies. Intercomparison with SINTEF's OSCAR model has already started, in collaboration with the University of Dalhousie (Li, 2017).

Another important limitation of the approach adopted is the fact that a purely deterministic strategy is adopted for the on-demand oil spill simulation systems. In that sense, the results presented are merely a "best-guess" solution, reducing options to the decision makers and responders. Providing probabilistic maps, capable of identifying confidence areas (or also usually called as "minimum-regret solution") where the probability of contamination is above specified thresholds, can represent an increase of the quality in the decision-making process, since prioritization is more straightforward. This probabilistic mapping for tactical response can be based in the inclusion of the uncertainties associated to the different parameters, metocean conditions and initial conditions used in the modelling process. Developing ensemble modelling through a stochastic approach, based in randomly-generated perturbations (according to the pre-determined uncertainties) in the oil spill model, could be a good strategy to accomplish the desired probabilistic mapping. One of the main challenges would be the computational performance, as this modelling procedure can be quite more demanding than the adopted deterministic approach. The other challenge would be the proper quantification of uncertainties. In the meanwhile, and during the course of this thesis, the development and implementation of ensemble probabilistic oil spill modelling based in uncertainties, has already been pursued by the author, in the scope of MARPOCS project (out of the scope of this thesis) (Fernandes, et al., 2016b).

In respect to the holistic risk modelling, some specific future improvements could significantly increase the final results. In the risk model adopted, there is no differentiation between identical ships from different countries, inspected at different ports, constructed or managed by different companies, or with different number of deficiencies detected in the recent past. This information is presently available online through EMSA's THETIS system, and in the future, interaction with this system can be seen as a relevant added value for integration in the risk model, if possible. Furthermore, the actual volume of contaminants, and product type transported by each ship is not included in the risk model, since the information is not publicly available (an approximation based on ship type and dead weight tonnage is adopted). The information would be rather important to improve the realistic quantification of estimated risk. Other improvement would be related to the application of the risk model developed: the system is prepared for the integration of high resolution metocean models, in order to provide specific and reliable risk studies in highly sensitive local areas.

Last, it should be noted the possibility of adapting the present holistic and dynamic risk approach to other environmental topics. Among these topics, one can mention: atmospheric dispersion from vessels; ballast water discharges and associated risks of spreading alien invasive species; marine litter; microbiological dispersion from wastewater treatment plants; and bathing water quality monitoring.

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Annexes

1 Processes and properties considered in MOHID oil spill fate and behaviour model

The algorithms, assumptions and detailed processes associated to MOHID oil spill model are described in this section. The most important oil physical and chemical transformations, as well as transport processes, have been included in MOHID.

Simulated processes include (three-dimensional) currents advection, spreading (on floating oil products), turbulent (vertical and horizontal) diffusion, evaporation from surface and consequent atmospheric transport, natural dispersion (droplets entrainment + submergence), dissolution, sedimentation (adsorption to sediments), and shoreline interaction. The significance of sedimentation as an important removal process depends critically on the sediment load of the surrounding water (typically, in open ocean, removal by sedimentation is trivial). Degradation (biodegradation and photo-oxidation) processes are not included in the model. Degradation can be considered significant only after the first week of simulation (Fernandes, 2001), which can be seen in Figure 8. For most oils, photo-oxidation is not a very well-known process, and is not considered an important process in terms of changing their immediate fate or mass after a spill. Biodegradation is not considered an important weathering process in the short term as well (Fingas, 2011a). The modelled oil properties along the simulation are the density and viscosity.

During the course of this thesis, several oil transport and weathering processes were either included, revisited, or adapted. The most relevant new processes added to MOHID oil spill model include the wave-induced currents (Stokes drift), leeward drift angle, dynamic estimation of wind drift coefficient, oil droplet 3D vertical movement (entrainment, resurfacing), atmospheric transport of evaporated fraction. New or newer formulations were included for evaporation, emulsification, shoreline interaction. The simulation of blowout emissions was also included in the model. Although this implementation was out of the scope of this thesis (Leitão, 2013), the simulation of this process was also improved by the work of the thesis, due to the new available formulations to compute oil droplet sizes and their ascending velocity.

1.1 Oil properties

The physical properties of the oil products change due to weathering processes suffered during the oil spill. For instance, evaporation will remove volatile (lighter components) from the sea surface, increasing the density; the formation of emulsions due to the incorporation of water in oil will increase the viscosity.

1.1.1 Density

Oil density is estimated in each instant considering the density of the emulsion at ambient temperature, the density of fresh oil at a reference temperature and the water temperature. The oil initial density is obtained from the algorithm proposed by the American Petroleum Institute (API).

API stands for the American Petroleum Institute, which is the major United States trade association for the oil and natural gas industry. The API represents about 400 corporations in the petroleum industry and helps to set standards for production, refinement, and distribution of petroleum products. One of the most important standards that the API has set is the method used for measuring the density of petroleum. This standard is called the API gravity, and is obtained as follows:

$$\text{API gravity} = (141.5/\text{Specific Gravity}) - 131.5 \tag{22}$$

Though API values do not have units, they are often referred to as degrees.

API specific gravity is also used to classify oil products in 4 different groups, as illustrated by the next table (ITOPF, 2016):

Table 23 – Different oil group types

	Oil groups			
	Group 1 (very light oils)	Group 2 (light oils)	Group 3 (medium oils)	Group 4 (heavy oils)
API gravity (15ºC)	>45.0	<45.0 and >35.0	>35.0 and < 17.5	< 17.5
Examples of oil products	Jet Fuels, Gasoline	Diesel, No. 2 Fuel Oil, Light Crudes	Most Crude Oils	Heavy Crude Oils, No. 6 Fuel Oil, Bunker C

Generally, when spilt, persistence increases with group number.

However, if an oil cools to below its pour point temperature, it will change from a liquid to a semi-solid.

In MOHID, only oil products with density lower than water are modelled, because higher density products will sink.

Oil density is calculated as follows (NOAA, 1994):

$$\rho_e = F_{wv} \cdot \rho_w + \rho_{oil}(1 - F_{wv})(1 + c_{DE} F_e)[1 - c_{DT}(T - T_0)] \tag{23}$$

where ρ_e is the density of the emulsion at temperature T, F_{wv} is the volume water fraction of the emulsion, ρ_{oil} is the density of fresh oil at reference temperature T_0, ρ_w is the water density, c_{DE} e c_{DT} are empirically fitted constants with values of $c_{DE} = 0.18$ and $c_{DT} = 8 \times 10^{-4}$, as suggested by NOAA (1994). The oil initial density is its API density.

1.1.2 Pour point

Another field in many oil property databases is the pour point of the oil. This is defined as the lowest temperature at which an oil will flow under specified conditions. Pour point is a difficult property to quantify and measurements of pour point vary widely.

The pour point for oil, unlike the melting point of a pure chemical, will increase as the oil weathers. Available formulas describe this change based on weathering processes (e.g. Mackay et al., 1983), but due to lack of comprehensive empirical parameters to a wide range of oil products, the pour point modification was not adopted in MOHID, which assumes a constant pour point.

1.1.3 Viscosity

The oil viscosity is controlled by three major factors: temperature, evaporation and emulsification.

The influence of temperature can be calculated by Andrade's correlation:

$$\mu = \mu_0 e^{c_t \left(\frac{1}{T} - \frac{1}{T_0} \right)} \tag{24}$$

Where μ is the oil viscosity (cSt) at temperature T (K), μ_0 is the initial oil viscosity (cSt) at reference temperature T_0 (K) and c_T is an empirical constant controlling the viscosity variation with temperature. A value of 5000 K is recommended by Lehr et al., 2002. Viscosity modification due to emulsification is defined by Mooney's equation (1951):

$$\mu = \mu_0 e^{\left[\frac{c_V F_{wv}}{(1-c_M F_{wv})}\right]} \quad (25)$$

Where F_{wv} is the volumetric water fraction of the oil water emulsion, c_V is an adimensional empirical constant controlling the effect of emulsion with a value of 2.5 recommended by Mackay et al., (1980). c_M is the Mooney's constant with a value of 0.65.

In MOHID, viscosity modification due to emulsification is alternatively determined by Fingas empirical results (Fingas, 2014), when the Fingas method is chosen by the end user. The viscosity modification (increase) is further described in 0, where an interpolated viscosity multiplier is obtained from Table 30.

The effect of evaporation on viscosity is calculated by the following equation (Mackay et al., 1980):

$$\mu = \mu_0 . e^{(c_E F_{em})} \quad (26)$$

F_{em} is the mass fraction of evaporated oil, and the adimensional empirical constant c_E varies with oil type, between 1 and 10, with higher values for more viscous products. The model assumes c_E = 10 when fresh oils at 15ºC have a cinematic viscosity greater than 38 cSt. In case of less viscous oils, c_E is estimated by a second-degree polynomial regression:

$$c_E = -0.0059.V_{cin15}^2 + 0.4461.V_{cin15} + 1.413 \quad (27)$$

where V_{cin15} is the oil cinematic viscosity (cSt) at 15ºC.

The three previous equations can be joined in the single viscosity equation (in the case of Fingas method is not used for emulsification):

$$\mu = \mu_0 . e^{\left[(c_E F_{em}) + \frac{c_V F_{wv}}{(1-c_M F_{wv})} + c_T\left(1/T - 1/T_0\right)\right]} \quad (28)$$

If Fingas method is used, then the equation will be:

$$\mu = \mu_0 . E_{Fingas} \cdot e^{\left[(c_E F_{em}) + c_T\left(1/T - 1/T_0\right)\right]} \quad (29)$$

Where E_{Fingas} is the interpolated viscosity multiplier obtained from Fingas in Table 30.

1.1.4 Surface tension

Surface tension / interfacial tension is the force of attraction between the surface molecules of a liquid. Laboratory data exist for the interfacial surface tension between oil and water.

Some spreading and dispersion algorithms require knowledge of an oil's surface tension. Mackay et al., 1982 have also proposed an algorithm to estimate surface tension evolution as a function of evaporation rate. However, other factors (not only weathering) can control the surface tension – for instance, some chemicals can be used to facilitate dispersion, reducing the oil surface tension.

In MOHID, interfacial tension is assumed as constant along the simulations.

1.2 Transport in water

Oil mass is transported in three-dimensional space and time (unless explicitly defined as floating oil). The horizontal movement is controlled by currents, wave-induced velocity (Stokes Drift), wind-drift velocity in the surface layer, spreading, and horizontal turbulence. The vertical movement depends on buoyancy, sinking velocity, turbulent dispersion, and also entrainment due to breaking waves. As wind increases, and / or breaking waves become more important, oil entrainment rate (natural dispersion) will tend to increase, and therefore, the vertical dimension of the oil movement becomes more important (Reed et al., 1999).

Previously mentioned horizontal and vertical components have duly been implemented in MOHID's lagrangian module, and are also used in the simulation of oil spills.

1.2.1 Currents

MOHID can simultaneously simulate currents (in the hydrodynamic module), or use an imposed solution (which is called the "offline" solution) from a previous run, or from a different model (or set of models), as long as the outputs accommodate the time period to simulate.

1.2.2 Mechanical spreading

Mechanical spreading is the horizontal expansion of an oil slick due to mechanical forces, such as gravity, inertia, viscous and interfacial tension. It is an important process in the early stages of oil slick transformation and is affected by the weathering processes, which tend to change the mass and physicochemical properties of the slick. In free-surface conditions the oil slick area also has a strong influence on the weathering processes, such as evaporation and dissolution, and because of this, slick area and thickness are key variables in oil weathering and transport models.

In case of an instantaneous spill, the initial slick area is determined by an equation deduced from Fay's solutions (Fay, 1969). Because the initial phase of the spreading (gravity-inertial phase) is too short, the initial area is calculated when that phase ends, and the gravity-viscous phase starts:

$$A_0 = \pi \frac{k_2^4}{k_1^2} \left(\frac{\Delta g V_0^5}{\nu_w} \right)^{\frac{1}{6}} \tag{30}$$

Where A_0 is the initial area of the spill (m^2), $\Delta = \frac{\rho_w - \rho_0}{\rho_w}$, ρ_w is the water density (g/cm^3), ρ_0 is the oil density (g/cm^3), g the gravity acceleration (m/s^2), V_0 the volume of spilled oil (m^3), ν_w the water kinematic viscosity and $k_1 = 0.57$ and $k_2 = 0.725$ (as recommended by Flores *et al*, 1998). The average oil thickness for each computational cell is estimated by dividing the sum of the volume of particles that have their centre of mass in the cell, by the cell area.

To simulate the oil spreading, a random velocity is added to the particles movement. The effect of this velocity reproduces the spreading effect, since it works as a diffusive term that reduces the thickness of the slick in time. The random velocity is calculated from the diffusion coefficient estimated from the Fay (1969) equation for the gravity-viscous phase.

$$k = \frac{\pi \cdot k_2}{16} \cdot \left(\frac{\Delta \cdot g \cdot V^2}{\sqrt{\nu_w}} \right)^{1/3} \cdot \frac{1}{\sqrt{t}} \tag{31}$$

The evolution in time of k (spreading diffusion coefficient) can be calculated in the following way.

$$a(t) = \frac{\pi \cdot k_2}{16} \cdot \left(\frac{\Delta(t) \cdot g \cdot V(t)^2}{\sqrt{\nu_w}} \right)^{1/3} \tag{32}$$

$$k(t) = \frac{a(t)}{\sqrt{t}} \tag{33}$$

$$k(t+\Delta t) = \frac{a(t+\Delta t)}{\sqrt{\left(\frac{a(t)}{k(t)} \right)^2 + \Delta t}} \tag{34}$$

If average oil thickness becomes too thin – less than a value between 0.1 and 0.01 mm, depending on product viscosity – oil spreading is stopped, according to Reed (1989) see table below.

Table 24 – Thickness limit for spreading (Reed, 1989)

API	Thickness limit [mm]
<17.5	0.1
>17.5 and < 45	0.157 – 0.0033 * API
>45	0.01

1.2.3 Turbulence

Turbulent transport is responsible for dispersion. The effect of eddies over particles depends on the ratio between eddies and particle size. Eddies bigger than the particles make them move at random, while eddies smaller than the particles cause entrainment of matter into the particle, increasing its volume and mass according to the environment concentration. The random movement is calculated following the procedure proposed by Allen (1982). The random displacement is calculated using the mixing length and the standard deviation of the turbulent velocity component, as given by the turbulence closure of the hydrodynamic model. Particles retain that velocity during the necessary time to perform the random movement, which is dependent on the local turbulent mixing length. The increase in volume is associated with small-scale turbulence and is reasonable to assume it as isotropic. Under these conditions, small particles keep their initial form and their increase in volume is a function of the volume itself.

Horizontal and vertical diffusion coefficients used in the determination of standard deviations can be parameterized by the end-user. Additionally, the standard deviation used for the vertical dispersion can optionally be automatically estimated based in a vertical profile of turbulence (depending on shear velocity).

1.2.4 Wave-induced velocity (Stokes drift)

Stokes drift velocity (or mass transport velocity) is the average velocity of a particle due to the orbital motions induced by waves (Stokes, 1847), in the direction of wave propagation. This velocity is calculated for each particle, and velocity components are then added to the horizontal velocities of the particle calculated in MOHID.

For instance, a particle floating at the free surface of water waves, experiences a net Stokes horizontal drift velocity in the direction of wave propagation.

The generic solution adopted for the determination of the Stokes drift velocity (u_s, in m/s) in MOHID is mathematically represented as (Daniel, 2003; Longuet-Higgins, 1953):

$$u_s = a^2 \cdot \omega \cdot k \frac{\cosh\left[2 \cdot k(z-h)\right]}{2 \cdot \sinh^2(k \cdot h)} + C \qquad (35)$$

Where h (m) is the water depth, z (m) is the depth below surface, a (m) is the wave amplitude ($a = H/2$), ω (rad/s) is the wave circular frequency ($\omega = 2\pi/T$) and k (m^{-1}) is the wave number ($k = 2\pi/L$) for waves with height H (m), period T (s) and wavelength L (m). C is a depth independent term:

$$C = -\frac{a^2 \cdot \omega \cdot \sinh(2 \cdot k \cdot h)}{4 \cdot h \cdot \sinh^2(k \cdot h)} \qquad (36)$$

In deep water ($kh >> 1$ or $h > L/2$), Stokes drift velocity becomes simply (Longuet-Higgins, 1953):

$$u_s = a^2 \cdot \omega \cdot k \cdot e^{-2kz} \qquad (37)$$

The wavelength can be read from a wave model output, or manually defined by end user. Otherwise, MOHID internally calculates wavelength based on an explicit approximation of the wave dispersion equation, proposed by Hunt's method (Hunt, 1979).

The direction of the Stokes' drift is set equal to the local wave direction. If wave parameters H and T are not available from a wave model, they can be defined by the end-user, or calculated inside MOHID, using simplified internal models based on wind, previously implemented.

An additional / alternative method was recently included in MOHID for the estimation of Stokes drift velocity, based in Ardhuin et al., 2009, with u meaning wind velocity (m/s) and H_s, the significant wave height:

$$u_s = 5.0 \times 10^{-4}[1.25 - 0.25(0.5T)^{1.3}] \cdot u \times min\{u, 14.5\} + 0.025(H_s - 0.4) \quad (38)$$

1.2.5 Wind-induced velocity

The advection of surface floating oil is subject to wind effects. The wind speed effect over the sea surface changes the hydrodynamic velocity, and its influence tends to decrease in speed and change in angle with increasing depth in the first few meters under the surface. In his classic theory of wind drift currents in an unbounded ocean infinite depth, Ekman assumed a constant value of vertical eddy viscosity. Under these assumptions the angle 0 between surface current and surface wind was 45º to the right of the wind direction in the Northern Hemisphere (Davies, 198). However, from observational evidence of oil movements summarized in Samuels, et al.,1982, it was suggested that an angle of between 10º and 25º is appropriate in a homogeneous sea.

Since the hydrodynamic models used to force oil spill models usually don't have enough vertical discretization to represent well the vertical shear at the scale of the floating oil slick thickness (between 1 cm and 0.01mm), oil spill models usually include wind-induced velocity represented by a wind drag coefficient (as a percentage of the wind speed), and a leeward drift deflection angle (clockwise in Northern Hemisphere), to account for the Coriolis effect during transport (National Research Council, 2003). Empirical studies in the 1960s established that oil slicks on a sea surface are transported with a surface current at 2.5 to 4% of the wind speed (Fallah and Stark, 1976; Reed, 1992). The wind drag coefficient has largely been taken as 3.5%, as a result of several measured experiments (Audunson et al., 1984; Youssef and Spalding, 1993; Reed et al., 1994). The deflection angle is usually assumed as a constant value. However, Youssef and Spalding, 1993 have provided calculated values for wind drag coefficient and deflection angle that vary with wind speed.

In MOHID, constant values can be assumed for wind drag coefficient and deflection angle. By default, wind drag coefficient is assumed as 3%, and wind deflection angle as 0º.

Alternatively, those parameters can also be computed as function of wind, according to Youssef and Spalding, 1993:

$$C_w = 3.9088 - 0.031885u \tag{39}$$

$$C_a = \begin{cases} 23.627 \text{ (when } u \leq 1\, m/s) \\ 23.627 - 7.97 \log u \; (when\; u > 1 m/s) \end{cases} \tag{40}$$

Where C_w is the wind drag coefficient (%); C_a is the wind deflection angle (degrees, clockwise in Northern Hemisphere); and u is the wind velocity (m/s).

As an additional alternative method, wind deflection angle can also be estimated by an empirical formula based on field observations and theoretical arguments, according to Samuels, et al.,1982:

$$C_a = 25\mathrm{e}^{\frac{-10^{-8}u}{\gamma g}}, \tag{41}$$

where $\gamma$is the kinematic viscosity of water (m²/s), and g is the gravitational acceleration (m/s²).

1.2.6 Natural dispersion: Vertical entrainment / droplets size

Oil can migrate to the water column due to breaking waves. This is called natural dispersion, moving lagrangian tracers from the surface to the water column.

Natural entrainment of oil can play an important role not only in mass balance calculations, but also in determining the spatial and temporal distribution of oil on the sea surface (Reed et al., 1999).

This is a vertical process, and therefore this tracer vertical movement is not considered when simulating explicitly floating oil, with all the tracers being kept at surface. Nevertheless, the mass transfer rate from surface to the water column (i.e., the entrainment or dispersion rate) is always quantified, independently from simulating explicitly vertical movements (3D) or not (2D).

- **Entrainment rate**

Since its implementation, MOHID is able to compute the entrainment rate using Mackay, 1980 approach, or the classic method from Delvigne and Sweeney, 1988.

The amount of oil dispersed in the water column using the formulation proposed by Mackay et al., (1980) is as follows:

$$\frac{dm_d}{dt} = 0.11 m_{oil} \frac{(1+W)^2}{1+50\mu^{1/2} h\sigma} \qquad (kg.h^{-1}) \tag{42}$$

where m_{oil} is the oil mass that remains on the surface (kg), μ is the oil dynamic viscosity (cP), h is the slick thickness (cm), W is the wind velocity ($m.s^{-1}$) and σ is oil-water interfacial tension ($dyne.cm^{-1}$). This equation represents a simplified algorithm for vertical dispersion as a function of the square of the wind velocity. The turbulent energy of the process is not considered.

This entrainment can alternatively be estimated by the approach of Delvigne & Sweeney (1988) and Delvigne and Hulsen (1994).

If the oil penetrates the water column after a surface spill, this means that the oil droplet will be subject to a vertical velocity, depending on the density differences and oil droplets diameter. The correct modelling of these processes forced the implementation of a three-dimensional modelling approach.

The Delvigne & Sweeney method can be used for vertical entrainment, represented as follows:

$$\frac{dm_d}{dt} = A_p \sum_{i=1}^{n} Q_{d_i} \tag{43}$$

This equation estimates mass transfer rate per time unit ($kg/m^2.s$). For each lagrangian particle, this is obtained from area of the particle times the sum of the various *(n)* entrainment rates Q_{di} ($kg/m^2.s$) for each droplet diameter interval (MOHID presently computes MOHID computes five particle diameter intervals; thus, $n = 5$):

$$Q_{d_i} = C^* \cdot D_{ba}^{0,57} \cdot f_s \cdot F \cdot d^{0,7} \cdot \Delta d \tag{44}$$

Where d is the droplet diameter (m), C^* is an empirical entrainment constant which depends on oil type and weathering state; f_s is the fraction of the sea surface covered by the chemical; D_{ba} is the dissipated breaking wave energy per unit surface area (J/m^2); F

is the fraction of sea surface hit by breaking waves, and d is the oil particle interval diameter (m), which is the oil droplet diameters range around d, equally distributed between minimum and maximum droplets diameters. The minimum droplet diameter entrained in the water column is assumed to be $0.1d_{50}$ (d_{50} (µm) is the mean droplet diameter of entrained oil), because volumes below this size are relatively small (about 2% of the volume in the mean size), and can be neglected. The maximum droplet diameters entrained in the water column is assumed to be the minimum of d_{50} and 70 µm. In numerical experiments and model testing, droplets larger than d_{50} or 70 µm were found to resurface in less than one time step and so are not quantified as separate surface slicks.

The mean droplet diameter of entrained oil, d_{50} (µm), was fit with a curve to data in Delvigne and Sweeney, 1988 to yield:

$$d_{50} = 1818 \cdot E^{-0.5} (\mu / \rho_0)^{0.34} \tag{45}$$

Where E is the energy dissipation rate per unit volume (J/m³·s) (according to Delvigne and colleagues values are between 10^3 and 10^4). A value of 5000 was adopted. μ is the oil dynamic viscosity (cP) and ρ_o is the density of the oil (g/cm³).

Using the data reported by Delvigne and Hulsen (1994), the entrainment constant, C*, was fit to the following logarithmic regression:

$$\text{If } (\mu / \rho) < 132 \text{ cSt, } C^* = \exp\left[-0.1023 \ln(\mu / \rho_0) + 7.572\right] \tag{46}$$

$$\text{If } (\mu / \rho) \geq 132 \text{ cSt, } C^* = \exp\left[-1.8927 \ln(\mu / \rho_0) + 16.313\right] \tag{47}$$

Where μ is oil dynamic viscosity (cP), and ρ and ρ_o are the density of the oil (g/cm³).

The dissipated wave energy, D_{ba} (J/m²), is:

$$D_{ba} = 0.0034 \rho_w g H_{rms}^2 \tag{48}$$

H_{rms} is the root mean square value of wave height (m), which can be obtained as follows:

$$H_{rms} = \frac{1}{\sqrt{2}} H_0 \tag{49}$$

where H_0 is the wave height (m).

The fraction of sea surface covered by breaking waves (whitecaps) per unit time, F, is parameterized as follows:

For $U_W <= U_{th}$ (Lehr et al., 1992):

$$F = 3\times10^{-6}(U_w^{3.5} / T_w) \quad (50)$$

And for $U_W > U_{th}$ (Delvigne & Sweeney, 1988):

$$F = 0.0032\left[(U_w - U_{th}) / T_w\right] \quad (51)$$

Where U_W is the wind speed at 10m above sea surface (m/s), U_{th} is the threshold wind speed for onset of breaking waves (~4m/s), and T_W is the significant wave period (s).

A more recent and alternative formulation for whitecaps is proposed by Callaghan et al., 2008.

$$W = 3.18 \times 10^{-3}(U_W - 3.70)^3; 3.70 < U_W < 11.25; \quad (52)$$

$$W = 4.82 \times 10^{-4}(U_W + 1.98)^3; 9.25 < U_W < 23.09; \quad (53)$$

, assuming that there are no white caps with wind speed below 3.70 m/s, and with W being the whitecaps, and

$$F = \frac{W}{T_W}. \quad (54)$$

This solution is limited to wind speed lower than 23.09m/s.

- **Determining if oil tracer stays at surface of entrains the water column**

In case of considering a 3D vertical movement, the first process to model is the entrainment of an oil tracer in the water column, which will be based on a random procedure. The probability of a tracer being entrained in the water column due to breaking waves is obtained from the instantaneous model "entrainment deficit" - difference between the theoretical fraction of dispersed oil estimated by one of the mass dispersion rate formulas described above, and the global mass fraction of entrained oil particles. Thus, the probability of a tracer entraining the water column is greater when the entrainment deficit is greater, i.e., when the difference between the global dispersion fractions obtained by the theoretical equations and the mass fraction of oil droplets in the water column is greater.

- **Droplets size**

Once a tracer is entrained in the water column, the next step is to decide the droplet diameter associated to the particle. Since a separation in different droplet diameter classes would imply a multiplication of the number of lagrangian tracers, each one representing a specific diameter class, MOHID selects only one single diameter class for each existing lagrangian particle. Three different approaches can be followed for this class selection:

a) each particle is assumed to have a typical user-defined diameter (default option = 0.05 mm, as proposed by Delvigne and Sweeney, 1988);
b) each particle is assumed to have a constant diameter equal to half of the mass median droplet diameter (d_{50}) (as proposed by Spaulding et al., 1992)
c) Assuming a specific number of different diameter classes, the total amount of entrained chemical substance per diameter class can be computed (using the previously mentioned Delvigne & Sweeney formulation); then a pseudo-random procedure can be used to select one diameter class, where the ones with higher amount of entrained chemical substance will have higher probability of being selected.

Model estimates a randomly distributed particle depth between 0m (surface) and the maximum intrusion depth D_i: (Tkalich and Chan, 2002):

$$D_i = 1.5\ H_0 \tag{55}$$

Where H_0 is the wave height (m).

If droplet particle diameters are smaller than 0.12 μm, then they are assumed to be operationally dissolved, according to North, et al., 2015.

Recently, a new semi-empirical model for oil droplet size distributions was proposed by Johansen et al., 2015, using empirical data obtained from laboratory experiments with different crude oils at different stages of weathering. This new model is a valid alternative to Delvigne and Sweeney approach, based on two major non-dimensional groups – the Weber number for the case limited by interfacial tension, and the Reynolds number for the viscosity-limited case, with the free fall velocity as the velocity scale and the oil film thickness as the length scale. A non-dimensional semi-empirical model was therefore formulated as an additive combination of the two cases, with two coefficients and one exponent determined by correlation with data from laboratory experiments.

This new model seems to cover a much larger range of oil viscosities than the model of Delvigne & Sweeney.

$$\frac{D}{h} = AWe^{-a}(1 + B'{V_i}^{a}) \qquad (56)$$

With a = 0.6, A = 2.251 and B'=0.027; *h* is the oil thickness (m), *We* is the Weber number:

$$We = \frac{\rho {U_H}^2 h}{\sigma} \qquad (57)$$

Where U_H is the free fall velocity(m/s), defined as:

$$U_H = \sqrt{2gH} \qquad (58)$$

With *g* being the gravity acceleration (m/s^2), and *H* being the free fall height or wave amplitude (equal to the double of the significant wave height, in m); and *Vi* is the viscosity number:

$$Vi = \frac{\mu U_H}{\sigma} \qquad (59)$$

With μ being the oil dynamic viscosity (kg/m.s), σ is the interfacial tension (N/m or kg/s^2).

- **Resurfacing**

After the migration of chemical tracers (droplets) to the water column, they will tend to ascend to the surface, due to its buoyancy. The droplet buoyant velocity is then integrated with the vertical advection and diffusion components (the advected vertical velocity – from the hydrodynamic solution – and the vertical turbulent diffusion velocity component). This means that in waters with higher turbulence, the buoyant velocity becomes less important.

The rising velocity can be based on the assumption that chemical particles can be represented as spheres of given diameter and density. Thus, buoyancy velocity w_s (m/s) will depend on density differences, droplet diameter *d* (m) and water kinematic viscosity v (m^2/s), as well as critical diameter d_{crit} (m) (Soares dos Santos and Daniel, 2000).

$$d_{crit} = \alpha \frac{v^{2/3}}{|g'|^{1/3}} \qquad (60)$$

where *g'* is the reduced gravity (buoyancy) (in m^2/s)

$$g' = g(1 - \frac{\rho_p}{\rho}) \tag{61}$$

If the particle's diameter is greater than d_{crit} then

$$W_s = \frac{g'}{|g'|}\sqrt{\beta d|g'|} \tag{62}$$

else

$$W_s = \frac{g'}{|g'|}\left(\frac{d^2|g'|}{18v}\right). \tag{63}$$

The values for α and β defined by default are 9.52 and 8/3, respectively, as proposed by (Soares dos Santos and Daniel, 2000). However, β is probably too large, overestimating buoyancy velocity for larger diameters (Zheng and Yapa, 2000). Thus, a value of 0.711^2 can optionally be used for β, and since parameter α is directly obtained by solving two previous equations for d, in this case, a value of 5.47 is used for α (Liungman and Mattsson, 2011).

The two equations previously presented for buoyancy velocity represent the large, spherical-cap bubble regime and the small spherical droplets (Stokes) regime.

Alternatively, a new formulation developed by Zheng and Yapa (2000) that considers three regimes was implemented. This formula considers that entrained droplets can behaviour in three different regimes - small spherical particles, intermediate ellipsoid bubbles and large spherical-cap bubbles.

- Regime of spherical shape (small size range):

$$U_T = \frac{R\mu}{\rho d} \tag{64}$$

The procedure to compute the Reynolds number R is shown below, according to Clift, et al., 1978):

Table 25 - Reynolds correlation, based on viscosity, density and diameter

Range (1)	Correlation (2)
$N_D \leq 73$	$R = N_D/24 - 1.7569 \times 10^{-4}N_D^2 + 6.9252 \times 10^{-7}N_D^3 - 2.3027 \times 10^{-10}N_D^4$
$73 < N_D \leq 580$	$\log R = -1.7095 + 1.33438W - 0.11591W^2$
$580 < N_D \leq 1.55 \times 10^7$	$\log R = -1.81391 + 1.34671W - 0.12427W^2 + 0.006344W^3$
Note: $N_D = 4\rho\Delta\rho g d_e^3/3\mu^2$ and $W = \log N_D$.	

Regime of ellipsoidal shape (intermediate size range):

$$U_T = \frac{\mu}{\rho d_e} M^{-0.149}(J - 0.857) \tag{65}$$

In which

$$J = 0.94H^{0.757}, \qquad (2 < H \leq 59.3) \tag{66}$$

$$J = 3.42H^{0.441}, \qquad (H > 59.3) \tag{67}$$

And

$$H = \frac{4}{3} EoM^{-0.149}(\mu/\mu_w)^{-0.14} \tag{68}$$

Where μ_w = dynamic viscosity of water (cP); M and E_o are computed by

$$M = g\mu^4 \, \Delta\rho/\rho^2 \, \sigma^3 \tag{69}$$

$$E_0 = g\Delta\rho \, d_e^2/\sigma \tag{70}$$

In which σ = interfacial tension (N/m). The criteria in this regime are $M < 10^{-3}$ and $E_o < 40$.

Regime of spherical-cap (large size range):

$$U_T = 0.711\sqrt{gd_e \, \Delta\rho/\rho} \tag{71}$$

The criterion for this regime is $E_o > 40$.

1.2.7 Atmospheric transport

If a specific fraction of the oil is evaporated, it is available for atmospheric transport. The oil is transported horizontally by the wind velocity and subject to (random) turbulent dispersion velocities in both the horizontal and vertical directions.

The following relationship between horizontal and vertical diffusion coefficients D_x, D_y and D_z and the turbulent velocity range [$-U_r$, U_r], [$-V_r$,V_r], [$-W_r$,W_r] (in m/s) is adopted according to Al-Rabeh et al.,2000)

$$U_r = \sqrt{\frac{6D_x}{\Delta t}} \tag{72}$$

$$V_r = \sqrt{\frac{6D_y}{\Delta t}} \tag{73}$$

$$W_r = \sqrt{\frac{6D_z}{\Delta t}} \tag{74}$$

Where Δt is the model time step (s).

Random velocities are therefore determined in the following way, like suggested by Proctor *et al.*(1994):

$$u_d = R_1 \cos(2\pi R_2) \cdot U_r \tag{75}$$

$$v_d = R_1 sen(2\pi R_2) \cdot V_r \tag{76}$$

$$w_d = R_3 \cos(2\pi R_3) \cdot W_r \tag{77}$$

where R_1, R_2 and R_3 are randomly generated numbers between 0 and 1.

The horizontal and vertical diffusion coefficients can be user-defined (constant) or internally estimated (variable), based on time and air stability:

$$D_x = \frac{\sigma_x^2}{2\Delta t},\ D_y = \frac{\sigma_y^2}{2\Delta t},\ D_z = \frac{\sigma_z^2}{2\Delta t} \tag{78}$$

Where σ_x, σ_y and σ_z are the diffusion parameters estimated by the following analytical formulas, assuming open-country conditions (NOAA, 2013):

Table 26 – Estimation of diffusion parameters for each stability class (NOAA, 2013)

Class	σ_x, σ_y (m)	σ_z (m)
A	$0.22\Delta x(1+0.0001\Delta x)^{-0.5}$	$0.20\Delta x$
B	$0.16\Delta x(1+0.0001\Delta x)^{-0.5}$	$0.12\Delta x$
C	$0.11\Delta x(1+0.0001\Delta x)^{-0.5}$	$0.08\Delta x(1+0.0002\Delta x)^{-0.5}$
D	$0.08\Delta x(1+0.0001\Delta x)^{-0.5}$	$0.06\Delta x(1+0.0015\Delta x)^{-0.5}$
E	$0.06\Delta x(1+0.0001\Delta x)^{-0.5}$	$0.03\Delta x(1+0.0003\Delta x)^{-1}$
F	$0.04\Delta x(1+0.0001\Delta x)^{-0.5}$	$0.016\Delta x(1+0.0003\Delta x)^{-1}$

Δx is the time step (m), and the (Pasquill) stability classes can be user-defined (constant), or computed (variable), under the following formulations for day and night (NOAA, 2013):

Table 27 – Estimation of stability classes during day time, based on wind and solar radiation conditions (EPA, 2000).

Wind speed (m/s)	Solar Radiation (W/m²)			
	≥925	675-925	175-675	< 175
< 2	A	A	B	D
2 - 3	A	B	C	D
3 - 5	B	B	C	D
5 - 6	C	C	D	D
≥ 6	C	D	D	D

Table 28 - Estimation of stability classes for night time, based on wind speed and vertical temperature gradient (EPA, 2000; NOAA, 2013)

Wind speed (m/s)	Cloud cover	
	>50%	<50%
< 2	E	F
2 - 3	E	F
3 - 5	D	E
5 - 6	D	D
≥ 6	D	D

Stability is D for completely overcast conditions.

1.3 Evaporation

The evaporation is computed from surface floating slicks.

In MOHID the oil evaporation process can be estimated by two different methods: an analytical method from Stiver & Mackay (1984), also known as the evaporative exposure method (based on an air-bounday-layer approach), and by a more recent methodology proposed by Fingas (1998), assuming a diffusion-regulated approach composed by many empirically developed equations for many oils, and where the relevant factors are time and temperature.

An alternate method – pseudo-component method of Jones, 1997 is commonly adopted on several oil weathering models (e.g. ADIOS2). However, it required considerable amount of input data (mean vapour pressure, solubility, molecular weight of each pseudo-component of the oil). Jones also found similarity between the results obtained for the pseudo-component method and Fingas method, and some slightly underpredicted results from Stiver & Mackay method. Due to the similarity of pseudo-component method and Fingas method; and since this latter and Stiver & Mackay method require both less detailed information on oil type and constituents, the pseudo-component was not encoded in MOHID.

Moreover, after comparison of the different modelling approaches and measured data, it was found that air-boundary-layer models result in erroneous predictions for several reasons: they cannot deal with long-term evaporation; the wind factor results in unrealistic values; and finally, they have not been adjusted for the different curvature for diesel-like evaporation (Fingas, 2011a).

1.3.1 Evaporative exposure method

The variation of volume fraction of evaporated oil (F_e) is given by:

$$\frac{dF_e}{dt} = \frac{K_e A_s}{V_0}.\exp\left(A - \frac{B}{T}\left(T_0 + T_G F_e\right)\right) \qquad (79)$$

Where T is oil temperature (ºC), A_s is the oil slick area (m^2), V_0 is the initial oil volume (m^3), A and B are empirical constants, T_0 is the initial boiling point (ºC) and T_G is the distillation curve gradient (ºC) and K_e is the mass transfer coefficient, determined by the formulation proposed by Buchanan & Hurford (1988):

$$K_e = 2.5 \times 10^{-3} W^{0.78} \tag{80}$$

Where W is the wind speed in ms^{-1}.

All these parameters depend on oil type. In this model, they are estimated, and A = 6.3, B = 10.3 (both empirical constants) (NOAA, 2000), T_0 e T_G are obtained from *API* density.

For crude oils (NOAA, 2000):

$$T_0 = 457.16 - 3.3447 \times API \tag{81}$$

$$T_G = 1356.7 - 247.36 \times \ln(API) \tag{82}$$

For refined oils (NOAA, 1994):

$$T_0 = 645.45 - 4.6588 \times API \tag{83}$$

$$T_G = 388.19 - 3.8725 \times API \tag{84}$$

1.3.2 Fingas method

Fingas (Fingas, 1995) has presented results that showed that the evaporation rates of oils and petroleum products are largely governed by temperature and time, and finding that the oil is not strictly boundary-layer regulated. This is a result of the fact that oil evaporation, especially after a short initial time period, is slower that the molecular diffusion rate of the evaporated components in the air. This has profound implications for most oils including:

- Area of the spill is not important to evaporation prediction
- Wind speed is not important
- Temperature is the most important environmental consideration
- Evaporation can be predicted for mass loss by equations of the form (following a logarithmic equation):

$$\%Ev = T \ln t \tag{85}$$

Where: $\%Ev$ is the percentage of mass evaporating per unit time, t; T is the Temperature and t is the time.

- Some diesel fuel oils and similar evaporate as a square root of time:

$$\%Ev = T\sqrt{t} \tag{86}$$

Several research from the author along the years resulted in a compilation of empirical equations following the previous forms, and adapted to a large number of oil products obtained from the experimental evaporation curves. These equations are listed in Fingas, 2011, for a wide panoply of oil products, under the forms:

- For oils that follow a logarithmic equation:

$$\%Ev = [B + 0.045(T - 15)] \ln t \tag{87}$$

- For oils that follow a square root equation:

$$\%Ev = [B + 0.01(T - 15)]\sqrt{t} \tag{88}$$

Where B is the equation parameter at 15ºC (available in Fingas, 2011), T is the temperature (ºC) and t is the time (minutes).

If the equation parameters are not available, the parameters can be estimated using distillation data, such as:

- For oils that follow a logarithmic equation:

$$\%Ev = [0.165(\%D) + 0.045(T - 15)] \ln t \tag{89}$$

- For oils that follow a square root equation:

$$\%Ev = [0.0254(\%D) + 0.01(T - 15)]\sqrt{t} \tag{90}$$

Where D is the percentage distilled at 180ºC, T is the temperature (ºC) and t is the time (minutes).

The previous method was fully encoded in MOHID.

1.4 Emulsification

This process, consisting in the incorporation of water in oil, is one of the most important weathering processes, because water-in-oil emulsions are a problem to clean-up due to the increase in viscosity and volume (viscosity can increase 1000 times). Emulsions had been studied extensively in the laboratory and field, thus many facets of their formation are now known.

Several oils do not form water-in-oil types until they lose a certain amount of volatile compounds through evaporation (Fingas, 2014). An emulsification constant is used in MOHID, which means the percentage of oil evaporated before emulsification starts. By default, this constant is 0%.

Some different algorithms and methodologies to estimate emulsification are included in MOHID model. The most recent method included is based on the empirical methodology developed by Fingas (2011) and recently updated in Fingas (2014), which was obtained based on 1500 laboratory and field tests conducted over more than 17 years and 400 oil products. This method is thus considered, at this moment, the state-of-the-art approach for the estimation of emulsification.

1.4.1 Fingas method

Fingas (2011) found that based on their stability, four clearly-defined water-in-oil types are formed by crude oil when mixed with water: stable and meso-stable emulsions, entrained water and unstable mixtures. The density, viscosity, asphaltene and resin contents were correlated to classify the emulsions on their previously mentioned stability classes, based on a stability index. A new complex procedure based on that assumption was obtained to predict the stability types / classes, and assigning values to increases in viscosity based on the class of emulsion formed. This new method is considered very much more accurate than the old methods.

Hence, as documented in Fingas (2014), the values from density, viscosity, asphaltene and resin contents can be used and / or transformed and then substituted in the following equation, to obtain the stability index, or stability classification:

$$\text{Stability Class} = -15.3 + 1010*Den - 3.66*Visc + 0.174*Rst - 0.579Ast + 34.4*(A/R) + 1.02*\exp(Den) - 7.91*\exp(A/R) - 2740*\ln(Den) + 12.2*\ln(Visc) - 0.334*\ln(Sst) - 3.17*\ln(Rst) + 0.99*\ln(Ast) - 2.29*\ln(A/R) \quad (91)$$

where: *Stability C* is the stability classification; *Den* is the exponential of density (density in mg/l), *Visc* is the natural logarithm (ln) of the viscosity (viscosity in mPa.s); *Rst* is the transformed resin content (%); *Ast* is the transformed asphaltene content (%); *A/R* is the unstransformed asphaltene/resin ration; *St* is the transformed saturate content (%). The above-mentioned transformations are:

- Transformed Saturate Content (%): If the saturate content is less than 45, then the saturate content parameter is 45 less the saturate content and if it is greater than 45, it becomes the saturate content less 45.
- Resin Content (%): If the resin content is less than 10, then the resin content parameter is 10 less the resin content and if it is greater than 10, it becomes the resin content less 10. If the value of the resins is zero, then this value is set to be 20.
- Asphaltene Content (%): If the asphaltene content is less than 4, then the asphaltene content parameter is 4 less the asphaltene content and if it is greater than 4, it becomes the asphaltene content less 4. If the value of the asphaltene content is zero, then the value is set to be 20.

The values of Stability Class assigned to each class of emulsion are given based in the associated conditions, as illustrated in the table below:

Table 29 – Relation of Stabilities to Water-in-Oil Type (Fingas, 2014)

Calculated Stability			
Minimum	**Maximum**	**Starting Oil Properties**	**Water-in-oil Type**
4	29		Stable
-10	5		Meso-stable
-20	3	**density >0.94 or <1.0** **viscosity > 6000**	Entrained
-4	-18	**density <0.85 or >1.0** **viscosity<100 or >800000** **Asphaltenes or Resins <1.5%**	Unstable

The next step is the prediction of the properties resulting from the water-in-oil emulsion – namely, the viscosity and water content. These properties can be taken as the interpolated values of the types at a given time as shown in the table below:

Table 30 – Viscosity increases from starting oil and typical water content (Fingas 2014)

	Viscosity increase on		
	First Day	**Week**	**Year**
Entrained	1.9	1.9	2.1
Meso-stable	7.2	11	32
Stable	405	1054	991
Unstable	0.99	1.0	1.0
	Typical water content		
	First Day	**Week**	**Year**
Entrained	44.5	27.5	6
Meso-stable	64.3	30	6
Stable	81	78	70
Unstable	6.1	6	5

Finally, the time to formation of the emulsions has also been previously studied by Fingas and Fieldhouse (2004), who related the time to formation of each emulsion type to the energy required for formation (expressed as equivalent wave height) and expressed as:

$$y = a + (b/x^{1.5}) \quad (92)$$

Where y is the time to formation (min), x is the wave height (cm), and a and b are coefficients depending on emulsion type, according to the following table:

Table 31 – Coefficients from equation to predict time to emulsion formation (Fingas and Fieldhouse, 2004)

Stability Class	Coefficients from equation $y = a + (b/x^{1.5})$	
	a	b
Stable	27.1	7520
Mesostable	47	49100
Entrained	30.8	18300
Unstable	0	0

1.4.2 Mackay method

Other alternative included in MOHID, is based in previous research work proposed by Mackay *et al* (1980):

$$\frac{dF_{wv}}{dt} = K_w (1+W)^2 \left(1 - \frac{F_{wv}}{F_{wv}^{final}}\right) \qquad (93)$$

Where W is the wind speed (m/s), F_{wv} is the water volume fraction incorporated into emulsion; F_{wv}^{final} is the final volumetric fraction of water incorporated in emulsion, K_w is an empirical constant, introduced by the user. Usually this constant assumes values between 1.0×10^{-6} and 2.0×10^{-6}. MOHID default value is 1.0×10^{-6}, which is also used in the ADIOS model (NOAA, 1994).

1.4.3 Rasmussen method

This method, also included in MOHID, is obtained from Rasmussen et al (1985), using the following equation:

$$\frac{dF_{wv}}{dt} = R_1 - R_2 \qquad (94)$$

where:

R_1 - Inflow rate (s^{-1}), given by:

$$R_1 = \frac{K_1}{\mu_0}(1+W)^2\left(F_{wv}^{final} - F_{wv}\right) \qquad (95)$$

R_2 - Outflow rate (s^{-1}), given by:

$$R_2 = \frac{K_2}{Asph \cdot Wax \cdot \mu_0} F_{wv} \qquad (96)$$

Asph is the oil asphaltene content (%); *Wax* is the oil wax content (%); K_1 and K_2 are constants experimentally determined by Rasmussen (1985) : K_1 = 5x10^{-7} kg.m^{-3} K_2 = 1.2x10^{-7} kg.m^{-1}.s^{-2}.

1.5 Dissolution

The dissolution rate (gh^{-1}) is the rate in which the soluble fraction of the oil breaks into small particles mixing with water forming homogeneous moisture between them. This rate is estimated in MOHID by the Cohen et al., (1980) equation:

$$\frac{dDiss}{dt} = K.f_s.A_s.S \qquad (97)$$

Where K is the dissolution mass transfer coefficient ($0.01 m.h^{-1}$), f_s is the surface fraction covered by oil (considered equal to oil content in emulsion water + oil); As is the oil slick area (m^2) and S is the oil solubility in water ($g.m^3$)calculated as proposed by Huang & Monastero (1982):

$$S = S_0.e^{\alpha t} \qquad (98)$$

where S_0 is the solubility of the "fresh" oil (30 $g.m^3$); α is a decay constant (0.1); t is the time after spill (h).

1.6 Sedimentation

Sedimentation is defined as adhesion of oil to solid particles in the water column. The significance of sedimentation as an important removal process depends critically on the sediment load of the surrounding water. For muddy rivers, where the sediment load can be more than 0.5 kglm3, the removal by sedimentation is considerable and exceeds the loss due to normal dispersion. For open ocean conditions, where sediment load is less than 1% of this amount, removal by sedimentation is trivial.

Although oil sedimentation process (adsorption to suspended particulate matter) is relatively difficult to estimate, the MOHID model uses a formulation developed by Science Applications International (Payne et al. 1987) for this purpose:

$$\frac{dm_{sed}}{dt} = 1.3\sqrt{\frac{E}{V_w}} K_a \cdot C_{oil} \cdot C_{sed} \cdot z_i \cdot A_s \qquad (99)$$

This equation gives the mass of "sedimented" (i.e., adsorbed to sediments) oil per time unit (kg.s^{-1}), where:

V_w is the water dynamic viscosity (kg.m^{-1}.s^{-1}); K_a is the sticking parameter with value 1×10^{-4} m^3.kg^{-1}; z_i is the intrusion depth of oil droplets in the water column due to breaking waves ($H_0$is the wave height, in m), given by Delvigne & Sweeney (1988):

$$z_i = 1.5 \cdot H_0 \qquad (100)$$

C_{sed} is the sediment concentration in water column (kg.m^{-3}), C_{oil} is the oil droplet concentration in water column (kg.m^{-3}). This concentration can be determined from dispersion rate proposed by Delvigne & Sweeney (1988) (explained in section 1.2.6), integrating this rate for wave period and intrusion depth of oil droplets:

$$\frac{dC_{oil}}{dt} = \frac{\frac{dm_d}{dt}}{z_i} \qquad (101)$$

E is the rate of dissipated energy from water surface (J.m^{-3}.s^{-1}):

$$E = \frac{D_{ba}}{z_i \cdot T_w} \qquad (102)$$

Where D_{ba} is the wave dissipation energy per unit of surface area (J/m^2), which can be calculated by the equation described in the “entrainment rate” section, from natural dispersion.

1.7 Oil beaching / shoreline interaction

When oil reaches a coastal zone, it might become beached, depending on shoreline and oil type. Oil loading on a shoreline can be highly variable, and the amount of oil and the rate of natural removal drive the decision to conduct shoreline clean-up. Once stranded on the shoreline, the oil is readily removed by tidal flushing and wave action.

The authors Reed and Gundlach, 1989 developed an oil-shoreline interaction model to predict the behaviour, loading, and fate of oil stranded on different shoreline types. It considers the oil density, viscosity, wave energy, grain size of shoreline sediments, and empirical holding thicknesses, penetration depths, and removal coefficients for each type of shoreline. This work provided the algorithms needed to improve the accuracy of oil fate models that previously did not fully consider the amount of oil stranded on a shoreline.

The same approach was also applied in MOHID. The model user predefines a timely-constant beaching probability (or different beaching probabilities for different coastal zones), as well as the distance to shoreline to be considered as beaching limit.

Each water grid cell close to the shoreline has a holding capacity volume, obtained from the area of that cell times the maximum surface oil thickness. This thickness is obtained as function of oil viscosity and shore type (see Table 32).

Table 32 - Maximum surface oil thicknesses for various beach types as a function of oil viscosity (source: Howlett, 1998)

Shore Type	Oil Thickness (mm) by Oil Type		
	Light (<30 cSt)	Medium (30-2000 cSt)	Heavy (>2000 cSt)
1. Exposed rocky shore	0.5	2	2
2. Gravel/cobble/boulder	2	9	15
3. Peat/tundra scarp	0.5	2	2
4. Sand beach	4	17	25
5. Mixed sand/gravel beach	2	9	15
6. Tidal flat	3	6	10
7. Wetland/marsh	6	30	40

When an oil particle reaches a grid cell close enough to shoreline (based on the beaching limit user-defined), it may become randomly beached, in accordance to the user-defined beaching probability, and only if the holding capacity volume for the shore in which contact has occurred has not been exceeded yet. By other words, oil volume may be deposited on the shore grid if the total volume accumulated is less than the holding capacity for that shore grid.

Once beached, the oil particle may also be removed / refloated on a rising tide (sufficiently high to wet the oiled surface) and offshore winds. The particle is then removed (based on a random procedure), taking into account that an empirical oil removal rate coefficient (based on exponential decay to characterize oil loss rate) can be defined either as constant in space (and by default, the oil removal rate is 0, i.e., there is no oil removal), or based on the shore type, as defined in the Table 33. The removal rate coefficient is expressed in days^{-1}, and reflects the amount of oil within the particular shoreline segment / computational cell, via application of the first-order equation defined as follows:

$$M_R = M_o e^{-K_f t} \tag{103}$$

Where M_R is the mass remaining on the shore at any time (kg); M_0 is the initial mass of oil deposited on shore (kg); t is the time (days) and K_f is the oil removal rate coefficient (days^{-1}).

Table 33 - daily oil removal rates as a function of shoreline type (CSE/ASA/BAT, 1986)

Shore type	Oil remove rate coefficient (days^{-1})
1. Exposed rocky	1
2. Wave cut platform	1
3. Fine sand	0.1-0.6 (~0.2)
4. Coarse sand	0.1-0.6 (~0.2)
5. Mixed sand/gravel	0.05-0.5 (~0.1)
6. Gravel/cobble	0.05-0.5 (~0.1)
7. Exposed tidal flats	1
8. Sheltered rocky	0.01-0.05 (~0.02)
9. Sheltered tidal flats	0.001-0.01 (~0.002)
10. Sheltered marsh	0.001-0.01 (~0.002)
11. Glacier	1

2 Background on risk of spill incident

Next table describes the types of incidents considered in the risk model, as well as the nomenclature used and the corresponding spill incident frequency constants (per distance unit navigated or annual frequency for illegal / operational discharges).

Table 34 - Different types of risk of spill incidents, and corresponding spill incident frequency constants.

Navigation	Type of incident	Risk index	Accident Frequency per km navigated
Ship navigating in restricted waters	Ship-to-ship collision	$I_{RSI\_CS2S\_restricted}$	3.52×10^{-7} (5)
	Collision with port facilities	$I_{RSI\_CPF\_restricted}$	4.22×10^{-7} (6)
	Grounding	$I_{RSI\_Gr\_restricted}$	2.83×10^{-7} (6)
	Fire & Explosion	$I_{RSI\_F\&E\_restricted}$	1.78×10^{-7} (5)
Ship navigating in unrestricted waters	Ship-to-ship collision	$I_{RSI\_CS2S\_unrestricted}$	1.26×10^{-8} (5)
	Foundering and structural failures	$I_{RSI\_Fo\_unrestricted}$	9.17×10^{-8} (6)
	Grounding during navigation	$I_{RSI\_GDN\_unrestricted}$	1.23×10^{-7} (6)
	Drift grounding	$I_{RSI\_DG\_unrestricted}$	1.89×10^{-8} (6)
	Fire & Explosion	$I_{RSI\_F\&E\_unrestricted}$	1.78×10^{-7} (5)
	Illegal / Operational Discharges	$I_{RSI\_IOD\_unrestricted}$	2.49×10^{-5} (6) (annual frequency)

In the determination of these risk indices for each type of incident, generic risk formula (sum of probability and severity indices) applies. Per example, for ships navigating in restricted waters, next formula represents the risk of spill incident from a ship-to-ship collision:

[5] Value adapted from IAEA, 2001

[6] Value extrapolated based on IAEA, 2001 and relations between annual frequencies from Filipe and Pratas, 2007

$$I_{RSI\_CS2S\_restricted} = I_{PSI_{CS2S\_restricted}} + I_{SSI_{CS2S\_restricted}} \tag{104}$$

Where $I_{PSI_{CS2S\_restricted}}$ and $I_{SSI_{CS2S\_restricted}}$ are the probability index and severity index (respectively) for ship-to-ship collision in restricted waters.

Integrated risk index is also determined (I_{RSI}), which means that we can also estimate the risk of an incident of a specific ship, independently of the type of incident. This integrated risk index is a sum of the various probability indices ($I_{\sum PSI\_restricted}$) with the weighted arithmetic mean of the severity indices ($\overline{I_{SSI\_restricted}}$) from the different types of incidents.

Thus, if a ship is navigating in restricted waters:

$$I_{IRSI\_restricted} = I_{\sum PSI\_restricted} + \overline{I_{SSI\_restricted}} \tag{105}$$

where $I_{\sum PSI\_restricted}$ is computed as follows:

$$I_{\sum PSI\_restricted} = f(P_{CS2S\_restricted} + P_{CPF\_restricted} + P_{Gr\_restricted} + P_{F\&E\_restricted}) \tag{106}$$

where $P_{CS2S\_restricted}$ is the probability of ship-to-ship collision in restricted waters; $P_{CPF\_restricted}$ is the probability of collision to port facilities in restricted waters; $P_{Gr\_restricted}$ is the probability of grounding in restricted waters; $P_{F\&E\_restricted}$ is the probability of fire and explosion in restricted waters

$\overline{I_{SSI\_restricted}}$ is computed as follows:

$$\overline{I_{SSI_{restricted}}} = \frac{(P_{CS2S\_restricted} \times I_{SSI_{CS2S\_restricted}}) + (P_{CPF\_restricted} \times I_{SSI_{CPF\_restricted}})}{\sum P_{restricted}} + \\ + \frac{(P_{Gr\_restricted} \times I_{SSI_{Gr\_restricted}}) + (P_{F\&E\_restricted} \times I_{SSI_{F\&E\_restricted}})}{\sum P_{restricted}} \tag{107}$$

Where $\sum P_{restricted}$ means the sum of probabilities in restricted waters.

Alternatively, if a ship is navigating in unrestricted waters, the same approach is followed:

$$I_{IRSI\_unrestricted} = I_{\sum PSI\_unrestricted} + \overline{I_{SSI\_unrestricted}} \tag{108}$$

Where $I_{\sum PSI\_unrestricted}$ and $\overline{I_{SSI\_restricted}}$ mean the sum of probability indices and the weighted arithmetic mean of severity indices, both in unrestricted waters.

$I_{\sum PSI\_unrestricted}$ is computed as follows:

$$I_{\sum PSI\_unrestricted} = f(P_{CS2S\_unrestricted} + P_{Fo\_unrestricted} + P_{GDN\_unrestricted} + P_{DG\_unrestricted} + P_{F\&E\_unrestricted} + P_{IOD\_unrestricted}) \tag{109}$$

Where $P_{CS2S\_unrestricted}$ is the probability of ship-to-ship collision in unrestricted waters; $P_{Fo\_unrestricted}$ is the probability of foundering and structural failures in unrestricted waters; $P_{GDN\_unrestricted}$ is the probability of grounding during navigation in unrestricted waters; $P_{DG\_runestricted}$ is the probability of drift grounding; $P_{F\&E\_unrestricted}$ is the probability of fire and explosion in unrestricted waters; $P_{IOD\_unrestricted}$ is the probability of illegal / operational discharge in unrestricted waters.

$\overline{I_{SSI\_unrestricted}}$ is computed as follows:

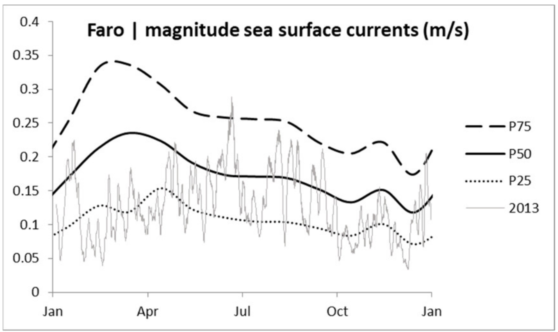
$$\begin{aligned}\overline{I_{SSI_{unrestricted}}} &= \frac{(P_{CS2S\_unrestricted} \times I_{SSI_{CS2S\_unrestricted}}) + (P_{Fo\_unrestricted} \times I_{SSI_{Fo\_unrestricted}})}{\sum P_{unrestricted}} + \\ &+ \frac{(P_{GDN\_unrestricted} \times I_{SSI_{GDN\_unrestricted}}) + (P_{DG\_unrestricted} \times I_{SSI_{DG\_unrestricted}})}{\sum P_{unrestricted}} + \\ &\frac{+(P_{F\&E\_unrestricted} \times I_{SSI_{F\&E\_unrestricted}}) + (P_{IOD\_unrestricted} \times I_{SSI_{IOD\_unrestricted}})}{\sum P_{unrestricted}}\end{aligned} \tag{110}$$

Where $\sum P_{unrestricted}$ means the sum of probabilities in unrestricted waters.

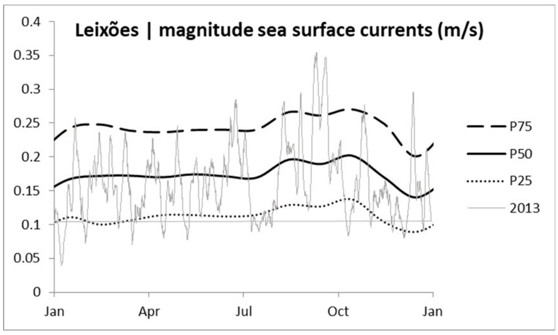
3 Metocean model data – comparison between 2011-16 period and 2013

This annex compiles the graphics obtained in the process of comparison of the metocean modelling data used as reference scenario (the year of 2013) in the scope of Chapter V.4 vs. the modelled data obtained from the period 2011-2016.

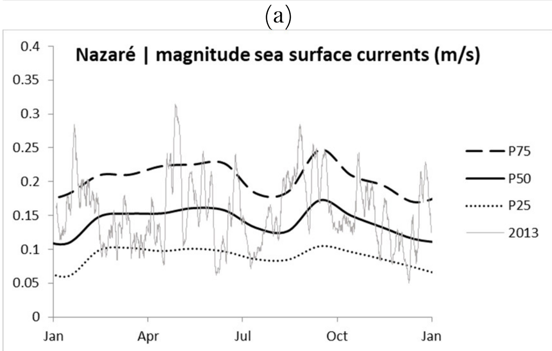
3.1 Sea surface currents (magnitude)



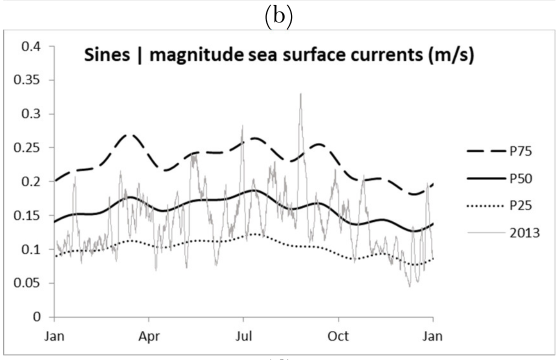
(a)



(b)



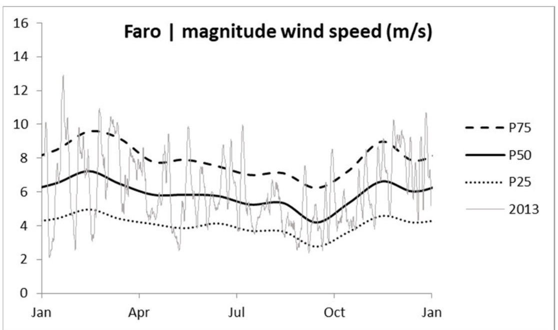
(c)



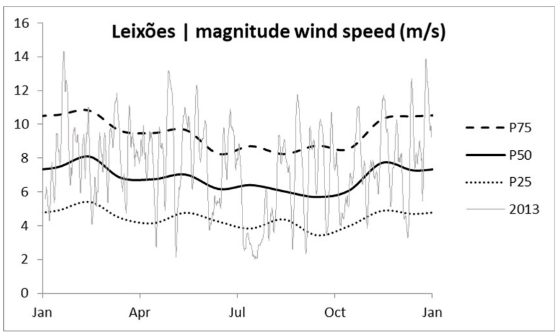
(d)

Figure 84 - Comparisons between sea surface current conditions (magnitude) in the periods 2011-2016 (monthly integrated data in percentiles) vs. 2013 (3-day moving averages), for locations close to Faro (a), Leixões (b), Nazaré (c) and Sines (d).

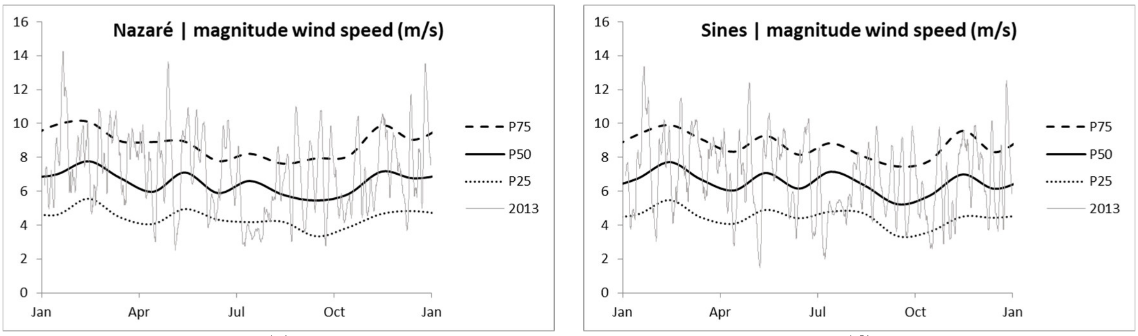
3.2 Wind speed (magnitude)



(a)



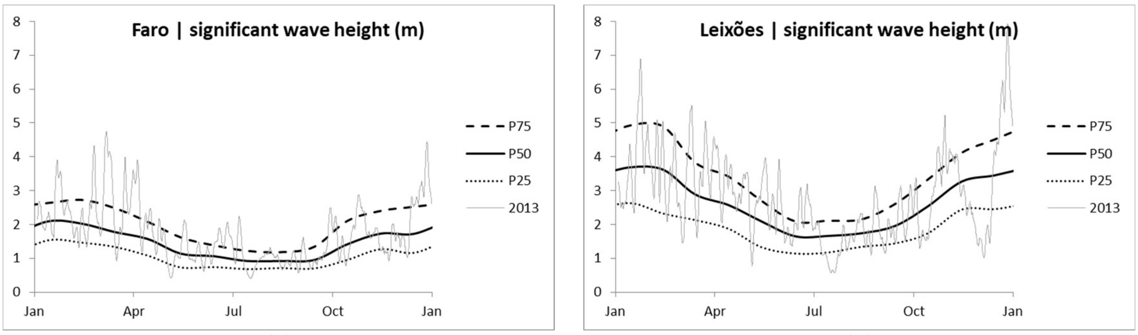
(b)



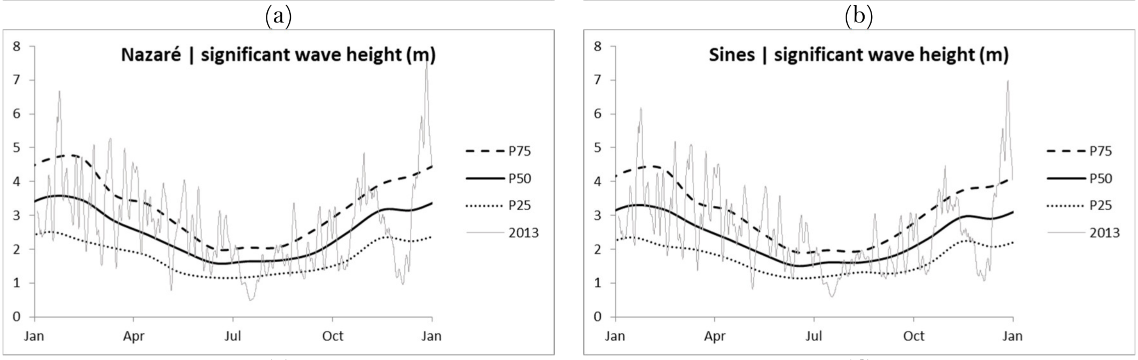
(c) (d)

Figure 85 - Comparisons between wind speed conditions (magnitude) in the periods 2011-2016 (monthly integrated data in percentiles) vs. 2013 (3-day moving averages), for locations close to Faro (a), Leixões (b), Nazaré (c) and Sines (d).

3.3 Significant wave height



(a) (b)



(c) (d)

Figure 86 - Comparisons between significant wave height in the periods 2011-2016 (monthly integrated data in percentiles) vs. 2013 (3-day moving averages), for locations close to Faro (a), Leixões (b), Nazaré (c) and Sines (d).